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Recent developments in anaerobic digestion technologies for energy recovery from industrial effluent and their applicability in Indian context

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Executive Summary

This work investigates the potential of bioenergy generation from the anaerobic digestion of industrial wastewater in India. It is estimated that up to 0.67 million ton LPG equivalent per annum of biogas can be produced by the treatment of agrobased industrial effluents alone, with distilleries and sugar mills contributing about 75% of this value. The technology is yet to be established in some highly polluting industries like tanneries and pulp and paper mills primarily since a majority of these plants are in the small and medium scale sector with poor waste management and resource recovery practices. Other industries like edible oil and coffee pulping units also produce wastewater which are amenable to anaerobic digestion but sufficient pilot testing is still lacking for commercial operation. It was also perceived that industries are hesitant to adopt this technology due to a combination of factors such as limited availability of experienced consultants to implement the technology, little full scale experience, lack of operator training within the industries for process maintenance and restricted technology transfer between research organizations and commercial developers/vendors. The Government of India is, however, actively promoting anaerobic digestion technology essentially from the viewpoint of establishing adequate wastewater treatment facilities. Apart from funding pilot studies, financial and fiscal incentives are also provided to both national and international entrepreneurs for establishing full scale plants based on proven anaerobic technologies.

1

Introduction

The generation and disposal of large quantities of biodegradable waste without adequate treatment results in significant environmental pollution. Besides health related problems for the populations near the sites where waste is dumped, further degradation of waste in the environment can lead to release of greenhouse gases such as methane and carbon-dioxide. In the absence of any waste treatment, as is normally the case, the environmental damage costs to the society works out to be more than the financial costs to the industry. Some of the waste streams are treated by conventional means such as aeration. This method is both energy intensive and expensive, and generates a significant quantity of biological sludge which must then be disposed off. In this context, anaerobic digestion offers potential energy savings and is a more stable process for medium and high strength organic effluents. Apart from treating the wastewater, the methane produced from the anaerobic system can be recovered. Besides reducing the amount of green house gases by controlled use of methane from waste, the substitution of oil and coal with bioenergy will result in saving the global environment by reducing the use of fossil fuel.

An increasing realization of the potential of anaerobic treatment is evident from the large number of recent research publications on this process. Till the seventies, aerobic processes were very popular for biological treatment of waste. The energy crisis in the early seventies coupled with increasingly stringent pollution control regulations brought about a significant change in the methodology of waste treatment. Energy conservation in industrial processes became a major concern and anaerobic processes rapidly emerged as an acceptable alternative. This led to the development of a range of reactor designs suitable for the treatment of low, medium and high strength wastewater.

The anaerobic process has several advantages over the other available methods of waste treatment. Most significantly, it is able to accommodate relatively high rates of organic loading. In addition, anaerobic digestion can be explored for bioreduction of organic materials that are not removed in conventional aerobic treatment. With increasing use of anaerobic technology for treating various process streams, it is expected that industries would become more economically competitive because of their more judicious use of natural resources. Therefore, anaerobic digestion technology is almost certainly assured of increased usage in the future. However, in spite of considerable interest and presence of technology vendors, potential users are often reluctant to adopt this technology for lack of detailed information concerning the process selection and performance standards from an independent agency other than the vendor.

With this background, this work aims to cover the following aspects :

a) Review of the current status in anaerobic treatment technology, both at the national and international levels

b) Suggest ways to adopt anaerobic digestion for industrial effluent treatment and

c) Identify problems and suggest future course of action in the Indian context in the light of current legislation and relevant standards of discharge.

The report is divided into five chapters. Chapter 2 presents an overview of the current scenario of industrial pollution, status of water quality and the actions initiated for the restoration of water quality in India. The regulatory and fiscal instruments and the discharge standards for selected industrial effluents are also given. In addition, the current activities initiated by the Government of India and institutional arrangements necessary for promoting rapid adaption of biomethanation technology by the industries are described. This chapter also touches upon the indigenous research and development work and provides an overview of biomethanation for domestic and industrial waste treatment in India.

A review of the types of anaerobic reactor systems, factors affecting anaerobic processes and the design principles of commonly used high rate anaerobic systems are described in chapter 3. The information provided in the chapter is gathered through electronic and manual literature searches and personal discussions with the subject experts during field visits.

Chapter 4 presents an assessment of the potential for energy generation through anaerobic digestion of effluents from various Indian industries viz. distillery, pulp and paper, sugar, dairy, coffee pulping, textile, slaughterhouse and edible oil manufacture. Each of these sectors is dealt with in detail with regard to the effluent characteristics and estimation of methane generation capability.

Finally, chapter 5 summarizes the main findings of this research work.

2

Industrial pollution & protection of water resources in India

Sources of pollution and water quality

India is bestowed with abundant water resources. Amongst India's water resources are 113 river basins of which 14 are major, 44 medium and the remaining 55 are minor basins. Large scale abstraction in the upper stretches and increased human and industrial activities along the banks have rendered most of the Indian rivers vulnerable to pollution and health hazards and made them unfit for designated use. Water resources are polluted through many and varied sources. The most critical are city sewage and industrial waste discharge. Sewage contributes about 60% of the total pollution load in terms of BOD (biochemical oxygen demand) (TERI 1998). Among the industrial sectors, water pollution is concentrated within a few industrial sub-sectors mainly in the form of toxic wastes and organic pollutants. Total wastewater generation from such major water consuming industries such as agrobased industries, refineries, petrochemicals, fertilizers, and industrial chemicals was estimated to be about 3000 million liters a day in 1997. Almost 65–70% of the organic pollutants released in the water bodies in the country are accounted for by food and agroproducts industries such as distilleries, sugar factories and pulp and paper mills (TERI 1998). Table 1 relates the share of industrial output to industrial pollution in India while Table 2 presents the details for agrobased industries. Table 3 summarizes the pollution load on the rivers in 22 critically polluted (industrialized zones) in India.

Table 1 Share of different industries in water pollution in India

Industry	*Share in terms of BOD* (%)
Industrial chemicals	29
Iron and steel	0
Non-ferrous metals	10
Other chemicals	1
Food products	38
Paper and pulp products	19
Non-metallic mineral products	0
Petroleum refineries	2
Textiles	1

Source World Bank 1996

Table 2 Water consumption, wastewater generation, and organic pollution load in agrobased industries

Industry	*Water consumption* (million litre per day)	*Wastewater generation* (million litre per day)	*Pollution load* (tonne biochemical oxygen demand per day)	*Share* (%)
Dairy	130	90	165	3 6
Edible oils and vanaspati	35	25	90	2.0
Fermentation (distilleries)	710	490	3290	71.4
Pulp and paper	820	685	1025	22.2
Starch (maize products)	4	3	24	0.5
Sugar	55	11	14	0.3
Total	1754	1304	4608	100.0

Source CPCB 1994

The present status of river water quality in India is shown in Figure 1. It is apparent that almost 80% of total river stretches in India are critically polluted signifying the need to apply conventional and/or tertiary treatment methods to make the water fit for household use. Eco-restoration of water resources has thus, become an urgent necessity.

Action plans for prevention and control of water pollution

India has initiated various programmes for improvement of water quality such as GAP (Ganga Action Plan) and the NRCP (National River Conservation Plan). The first phase of GAP was launched in July 1985 with the main objective of pollution abatement of the river Ganga from domestic and industrial sectors. The main achievements of GAP are (MoEF 1998) :

- Laying of 385 km of intercepting sewers
- Setting up of 35 large and medium sewage treatment plants which will treat about 882 MLD (million litres per day) sewage
- Capacity creation to treat 229 MLD of industrial waste
- Successful development of new technologies like UASB (upflow anaerobic sludge blanket reactor) as well as sewage treatment through afforestation
- Demonstration of resource recovery options like production of methane for energy generation and use of aquaculture for revenue generation and
- Complete ban on the use of DDT and phasing out of BHC in agriculture.

Table 3 Some critically polluted industrial areas in India

Area	*Receiving water body*	*Organic pollution load* (tonne/day)
Chembur, Maharashtra	Mahul Creek	70
Durgapur, West Bengal	Damodar	Not available
Korba, Madhya Pradesh	Hasdeo	3
Manali, Tamil Nadu	Buckingham canal	11
Singrauli, Uttar Pradesh	Rihand reservoir	30
Talcher, Orissa	Nandira	1210
Bhadravati, Karnataka	Bhadra	8
Vishakhapatnam, Andhra Pradesh	Bay of Bengal	35
Greater Cochin, Kerala	Periyar	1
Digboi, Asssam	Digboi	0.2
Nagda-Ratlam, Madhya Pradesh	Chambal	6
Dhanbad, Bihar	Damodar	180
Najafgarh, Delhi	Yamuna	165
North Arcot, Tamil Nadu	Palar	29
Vapi, Gujarat	Kolak and Damanganga	50
Pali, Rajasthan	Bandi	9
Patancheru, Andhra Pradesh	Manjeera	*
Parwanoo, Himachal Pradesh	Kaushalya	2
Kal Amb, Himachal Pradesh	Markanda	2
Jodhpur, Rajasthan	Jojri	2

* Pollution may be due to heavy metals

Source CPCB 1992

GAP has been extended to its second phase to cover (1) the left over works of Phase I on the main stream of the river Ganga, and (2) works on the major polluted tributaries namely, the Yamuna, the Gomti and the Damodar. Learning and gaining experience from GAP, the GoI (Government of India) has extended the scheme with suitable modifications to NRCP. The prioritization of river stretches is based on scientific criteria like the evaluation of WQIs (water quality indices) as well as on availability of funds. The programme is scheduled to be completed by the year 2006. As with rivers, India has proposed to launch a National Lake Conservation Plan for all the major polluted lakes in India. The plan will cover 10 lakes in 9 states and union territories with the estimated cost of implementing the scheme being Rs 6370 million (MoEF 1998).

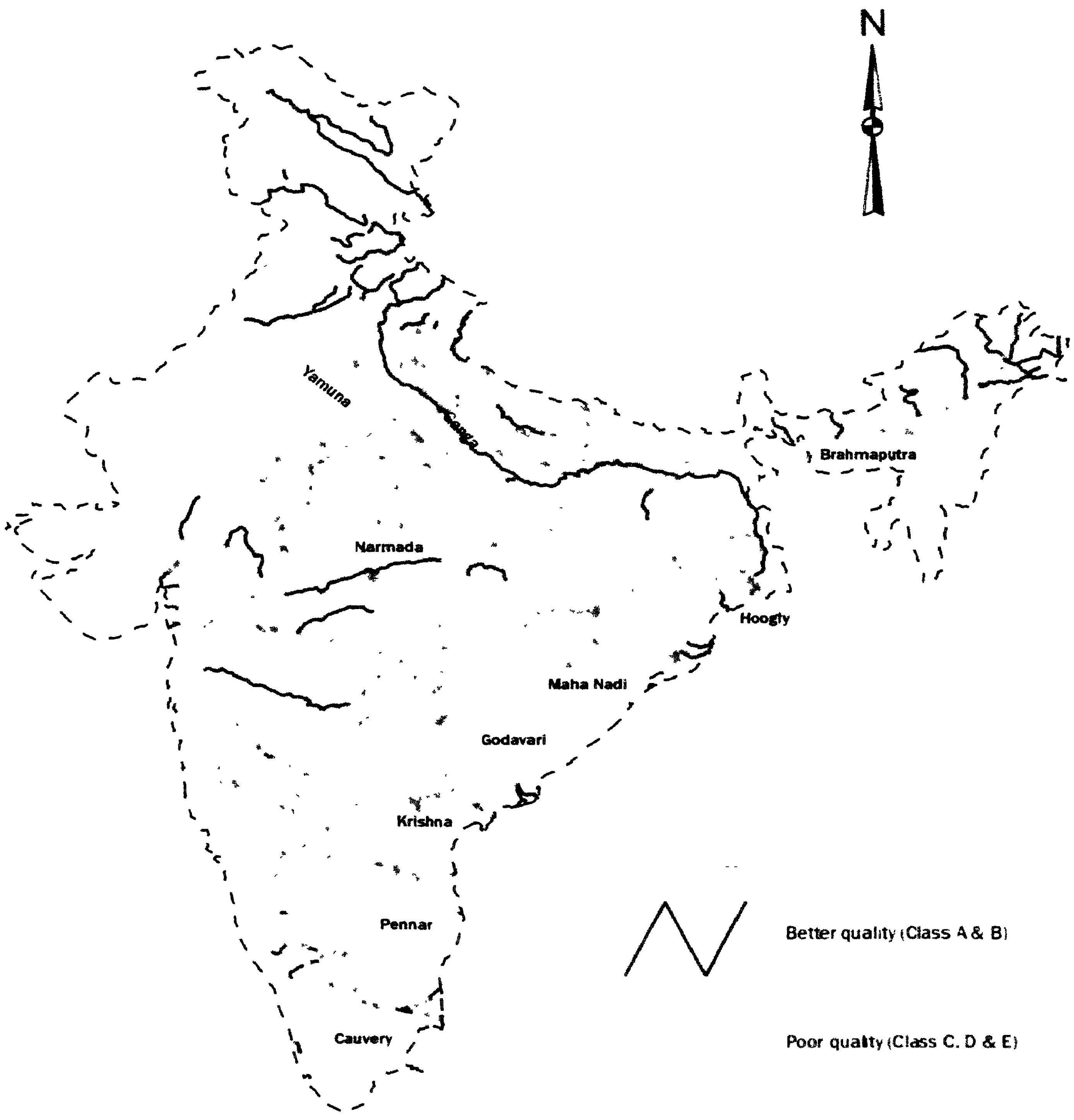
To control pollution from industries, the MoEF (Ministry of Environment and Forests), under the EPA (Environment Protection Act) 1986, has framed the MINAS (minimal national standards) to be followed by all industries in the country. The standards have been formulated for discharge of effluents from various types of industries and have been prescribed after a comprehensive techno-economic evaluation. The wastewater discharge standards for selected industries are given in Annexure I (CPCB 1995a). Recently, massbased standards have been laid down to set specific limits to encourage the minimization of waste and promote recycling and reuse of materials. Thus, for the most polluting industrial processes, the standards require the application of the best available technological solutions, and thus are an instrument for technological upgradation.

The CPCB (central pollution control board) has selected 17 categories of major polluting industries for priority action. The Ministry has initiated a 15-point action plan to control pollution and directed the SPCBs (state pollution control boards) to ensure the compliance of standards by these industries. The status of pollution control in these industries is shown in Table 4. More than 50% of the units in four categories namely distillery, pulp and paper, textile and iron and steel, are yet to attain satisfactory performance level with regard to installation and operation of ETP (effluent treatment plants) and emission control systems. The GoI has planned to undertake the following activities during the Ninth Five-Year Plan (1997–2002) (MoEF 1996):

- Continuation and consolidation of the ongoing programme for river-quality monitoring
- Launching a scheme for water-quality monitoring in medium and small rivers, establishment of a network for monitoring groundwater quality
- Action plans for phasing out of polluting technologies/toxic products
- Waste minimization and waste utilization
- Institutionalization of waste minimization circles among the clusters of small-scale industries
- Continuation of existing fiscal incentives for pollution abatement and extension of incentives for generation of useful products from wastes and substitution of environmentally-harmful inputs like chemical fertilizers and pesticides
- Promotion of participatory programmes for enlisting public support and involvement in cleaning of neighborhood areas.

notion of biomethanation technology in India

For the past many years, anaerobic digestion has been used in India as a low cost method of treatment for the stabilization of sewage sludge and sewage. India is perhaps next only to China, as far as anaerobic digestion of animal dung in smallscale plants is concerned. To meet the growing energy needs of the country,



Source
Survey of India, Dehra Dun
Central Pollution Control Board, New Delhi
TERI, New Delhi

Figure 1. An overview of water quality in major river systems of the count

Table 4 Pollution control systems in some major polluting industries

Category of industry	*Total units*	*Percent of industries with ETP*
Caustic soda	13	92
Cement	253	55
Dairy	127	69
Distilleries	218	50
Fertilizers	108	69
General Engineering	851	78
Integrated iron and steel	237	34
Inorganic chemicals	442	8
Manmade fibre	16	75
Mining	77	44
Oil Drilling	15	73
Pulp and paper	279	32
Pesticide	70	73
Petrochemical	67	36
Pharmaceutical	256	80
Refinery	26	50
Rubber products	118	64
Sugar	393	74
Tannery	85	62
Textile	559	44
Thermal power	87	70

Source CPCB 1997

GoI has placed growing emphasis on new and renewable sources of energy (NRSE) as is evident by growing financial outlays earmarked for the seventh (Rs. 5.8 billion) and eighth five year (Rs. 8.51 billion) plans (UNDP 1994). During the eighth plan period, Rs. 3.2 billion were allocated for promotion of biogas through the concerted efforts of the MNES (Ministry of Non-Conventional Energy Sources). So far, 2.7 million biogas plants have been installed in India, with a further potential to install 1200 million plants (MNES 1998).

The GoI under the chairmanship of Secretary, MNES has set up the NBB (national bio energy board) on April 1 1994 as the National Apex Agency for providing policy guidelines and directions for harnessing bioenergy from urban, municipal and industrial wastes. A `National Pilot Programme' on energy recovery from urban, municipal and industrial wastes covering all States and Union Territories was launched in 1995. The programme aims at promotion, development, demonstration, dissemination and adoption of appropriate conversion technologies for both solid and liquid wastes through improved waste management and introduction of fiscal and financial incentives. Projects utilizing wastes from urban, municipal and industrial sectors for energy recovery would be set up under the National Programme (MNES 1995). The overall goals and objectives of the programme include :

- Creation of conducive conditions & environment, with fiscal and financial regime to help promote, develop, demonstrate and disseminate utilization of waste for recovery of energy and resources
- Improving the waste management practices through adoption of technologies for conversion of such wastes into energy
- Promote setting up of projects utilizing wastes from urban, municipal and industrial sectors.

In addition, MNES has initiated a project partially assisted by UNDP/GEF on the development of high rate biomethanation processes as a means of reducing greenhouse gas emission. This is scheduled to be completed by September 1 1999 and has a total outlay of Rs 40 crore. The project covers up-scaling, validating and nearly full-scale demonstration of mature technology. The overall objectives of the scheme are :

- Develop institutional framework at national level to generate necessary awareness and capabilities to provide impetus to the Bioenergy Development Programme utilizing high rate biomethanation processes
- Develop requisite expertise and capabilities in the national and state level institutes, R&D organizations and universities to assimilate and adapt technologies, improve applied R&D skills in the field of high rate biomethanation processes, and to provide technical knowhow and assistance in setting up plants using the biomethanation process
- Promote the use of biomethanation technology and biogas utilization as cost effective means of energy generation through demonstration sub-projects and national and local level seminars and workshops, promotional campaign, training and demonstration; and
- Develop a national master plan and a shelf of investment proposals to utilize this important renewable resource through commercialization of processes.

The scheme which originally planned to cover sixteen demonstration sub-projects has been expanded to a total of 29 sub-projects in nine sectors viz.

sewage (3), pulp and paper effluents (3), vegetable market wastes (6), leather effluent/abattoir wastes (6), biogas utilization for power (4), food and fruit processing industry waste (2), municipal solid wastes (2), dairy wastes (1) and animal waste and agroresidues (2) (MNES 1998). Of these, four sub-projects e.g. (i) biomethanation of sewage treatment (ii) biomethanation for treatment of slaughter house waste (iii) biomethanation of paper mill black liquor and (iv) evaluation of biomethanation systems have already been completed.

Financial incentives for promotion of biomethanation

Some of the major incentives for the promotion of biomethanation technology are listed below:

- Interest Subsidy i.e. 10% on the loan amount for the entire loan repayment period, subject to maximum capitalized amount of Rs 1.0 crore per MWe (mega watt electricity)
- Investment Subsidy i.e. 50% of direct equity stake in the project cost limited to Rs. 1 crore/MWe
- Rs. 15.00 lakh per MWe to municipal corporations/urban local bodies, subject to their co-ordinated actions for finalization of clearances/agreements for making land available at token lease rent for minimum lease period of 30 years, garbage available free of cost at project site and for power purchase/sale
- Rs 5.00 lakh per MWe to state nodal agencies subject to their involvement in actions indicated above
- A sum of 2% of the interest subsidy channelized through the lead financial institution, as service charges, subject to a maximum of Rs. 2.00 lakhs per project on reimbursement basis
- SEBs (State Electricity Boards) are eligible for the following incentives for the waste to energy projects:
  - 25% of cost of equipment for interconnection/evacuation facilities (max Rs. 1.5 lakh per MW)
  - Cash incentive for power fed in to grid.
    First 50 million units/year - 5 paise/unit
    Next 100 million units/year - 4 paise/unit
    Next 150 million units/year - 3 paise/unit
- Preparation of DPR/TFR etc. 50% of the cost subject to a maximum of Rs. 2.0 lakh detailed project report/technical feasibility report
- Financial support of up to 50% of project cost limited to Rs. 3.0 crore/MW including the cost of land as per revenue records for setting up innovative demonstration project(s) based on emerging technologies/packages
- Cost sharing of up to 50% of the incremental capital cost of power generation system at STPs (sewage treatment plants).

Fiscal Incentives

The following tax benefits are applicable to biomethanation projects:

- Accelerated 100% depreciation in the first year
- Tax holiday for 5 years
- No excise duty on gas engines and municipal waste conversion devices producing energy
- Concessional custom duty of 10% for all goods, imported by a manufacturer/supplier for the manufacture and supply of machinery and equipment to a power generating plant (other than captive power generating plant)
- Concessional customs duty (20% custom duty+13% CVD) on project import.

Eligibility Criteria

The following categories are covered under this plan:-

Promoters. Private and public sectors, entrepreneurs/investors including urban local bodies, institutions, associations, individuals or group of individuals, etc. financially sound to make promoter's equity contribution (satisfying the criteria of financial institutions) and possessing technical capability to implement projects with improved waste management systems.

Wastes. Any waste or mix of waste(s) of renewable nature from urban, municipal & industrial sectors (other than bagasse, spent wash, wastes/residues, or derivatives from conventional sources viz. coal rejects, wood dust etc.).

Technologies. Any conversion technology like biomethanation, pelletization, gasification, pyrolysis, incineration, sanitary land filling, etc. or their combination.

Capacity . Waste to energy in the form of solid fuel: 15 TPD (tonnes per day) output, Waste to Energy in the form of Gaseous fuel: 50 m^3/hour, Waste to Energy in the form of Electricity: 100 KW, Waste to Energy in combined form: 100 kwe.

Anaerobic treatment systems in India - current status

Considering the overall deterioration of the quality of water resources, it is of utmost importance to find consistent long term solutions. In the recent past, there has been an exponential growth in the application of anaerobic technology, both for municipal and industrial wastewater treatment. The most widely used designs have been the upflow anaerobic sludge blanket, fixed film and expanded fluidised bed reactors. For instance, a 0.4 MLD capacity sewage treatment plant based on fixed film reactor has been installed at the Regional Research

Laboratory, Bhubaneshwar under the UNDP-GEF assisted programme. Apart from small scale demonstrations, a number of full scale treatment units are also being built, several of them under various river action plans. The world's first full scale UASB demonstration plant for municipal wastewater was built in Kanpur, Uttar Pradesh in 1989 under the Indo-Dutch Project and has been in operation since then. The plant is designed to treat 5 MLD domestic wastewater and the reported biogas yield is 0.1–0.15 m^3/kg COD removed with a methane content of 75–80 % (Khan 1995). The performance data of the plant is presented in Table 5.

Table 5 Performance data of the 5 MLD UASB demonstration plant at Kanpur

Parameter	*Concentration* (mg/litre)		
	Influent	*Effluent*	*Removal efficiency* (%)
COD	552	136	75.3
BOD	222	44	80.2
TSS	322	68	78.9

Subsequently, under the same project, a 14 MLD unit was designed and built in Mirzapur, Uttar Pradesh and another 36 MLD unit has also been operational since March 1995 in Kanpur (Tare, Mansoor and Mohammad 1997). The performance of the plants is summarized in Table 6. A similar plant of 50 MLD capacity is now being built to treat the sewage for Hyderabad city (Arceivala 1995).

Table 6 Performance of full-scale anaerobic reactors treating municipal wastewater

Parameters	36 MLD, Kanpur (Prasad 1995)	14 MLD, Mirzapur (Hammad 1996)
Volume, m^3	12000	4800
HRT, h	8	8
Organic loading, kg COD/m^3d	5.625	1 10
Upflow velocity, m/h	0.92	0 61
COD removal, %	24-50	49-65
BOD removal, %	25-47	58-71
TSS removal, %	29-73	50-76
Effluent COD, mg/litre	551-730	133-254
Effluent BOD, mg/litre	220-303	58-84
Effluent TSS, mg/litre	220-825	91-148

High rate anaerobic treatment technologies have also been adopted by several Indian industries. Different reactor designs like UASB (Jalgaonkar 1995), hybrid reactor (Bardiya, Hasia, Chandra 1995) and fixed film reactor (Manihar 1995) have been employed for distillery and sugar waste treatment. Currently, there are two full scale plants which are operational for the treatment of pulp and paper mill effluent. A CSTR type anaerobic treatment plant has been installed in Pudumjee Pulp and Paper Mills, Pune to treat around 250 m^3 effluent per day with a BOD and COD removal of approximately 85 and 65% (personal communication). Recently, a 4.58 MLD wastewater treatment plant based on UASB technology has been successfully commissioned at Satia Paper mills, Punjab (Bioenergy News 1997). A commercial tannery at Kanpur has installed a 10,000 litre capacity UASB reactor. With a HRT of 12 h, the plant was able to achieve 70% reduction in COD (Rajamani, Suthantharajan and Ravindranath 1995). The sludge produced was stable, less in volume and had good dewatering capacity. Yet another sector is the dairy industry which produces large amount of wastewater suitable for anaerobic treatment and controlled methane production. Extensive pilot plant studies in the state of Maharashtra were carried out to develop an anaerobic treatment process for dairy wastewater (Amritkar 1995). A case study in a milk-processing unit in Maharashtra showed that through anaerobic treatment, savings to the tune of Rs.25 million per year can be achieved in Maharashtra alone (Amritkar 1995).

In addition to commercial operations, several laboratories in India are actively involved in the research and development of anaerobic treatment systems. Annexure II highlights the R&D projects sponsored by MNES, Government of India over the last 15 years. More than half (62%) projects were devoted to research while the remainder dealt with demonstration and evaluation of the technology. Though there are several anaerobic wastewater treatment plants commissioned by private companies and individual entrepreneurs, similar details could not be obtained for those systems.

3

Developments in anaerobic digestion technologies

Conventional digesters such as sludge and anaerobic CSTR (continuous stirred tank reactors) have been used in India for many decades in sewage treatment plants for stabilization of the activated sludge and sewage solids. The area is well researched and sufficient information and operating experience is therefore available on the subject. In recent times, the emphasis has shifted to high rate biomethanation systems which are based on the concept of sludge immobilization techniques (UASB, fixed films etc). This chapter presents an overview of the developments in anaerobic treatment technologies as well as the factors affecting the system operation.

Historical development

It was a long accepted belief that anaerobic digestion was feasible only for the treatment of concentrated wastes such as manure and sewage sludge with long retention times (Table 7). Around 1950, anaerobic treatment of wastewater was attempted and the concept of high rate systems received importance with the use of mixing devices in the digester to break scum and increase contact between organisms and the substrate. Special reactor types for wastewater treatment such as the anaerobic contact process were also developed. The energy crisis in 1973 strongly augmented the interest in anaerobic digestion for all biodegradable wastewater. Advanced methods such as the upflow anaerobic sludge blanket (UASB) process and various fixed film reactor types based on the principle of sludge immobilization were introduced at this point. At present, anaerobic digestion has become a popular option and is a widely used wastewater treatment method.

The main advantages of anaerobic treatment in comparison with aerobic wastewater treatment are:

- Lower energy requirements combined with the production of biogas
- Low nutrient requirement
- High degree of waste stabilization
- High organic loading rates
- Lower production of excess sludge, which in addition is well stabilized and therefore easier to dispose and
- Easier preservation of well adapted sludge which can be kept unfed for a period of more than one year without any deterioration.

In view of its simplicity and low capital cost combined with its energy recovery capability in the form of biogas production, anaerobic digestion technology has received considerable importance in developing countries like India.

Table 7 Developments in anaerobic digestion

Investigator	*Process description*
M. Louis Mouras (1881)	Mouras-Automatic Scavenger
W.D. Scot-Moncrieff (1880) England	The first application of an anaerobic filter
Donald Cameron (1883) England	Septic tank
At Matunga, Bombay (1897)	Waste disposal tanks at leper colony with gas collectors
Harry W Chark (1899) USA	Sludge was formed in a separate tank
William O. Travis (1904)	Travis tank with hydrolyzing chamber
Karl Imhoff (1905)	Modification of Travis tank
Germany (1927)	The first sludge heating apparatus in a separate digestion tank was set up. The collected gas was delivered to municipal gas system.
Fair and Moore (1930)	Importance of seeding and pH control
Morgan and Torpey (1950)	Mixing in digester and development of high rate digestion
Stander (1950)	Development of Clarigester and anaerobic baffled reactor based on RBC concepts
Young and McCarty (1969)	Anaerobic filter
Lettinga (1979)	UASB
Switzenbum and Jewell (1980)	Developed the further concept of anaerobic filters to fixed film reactors

Source Khanna 1989

Factors affecting anaerobic processes

The course of the anaerobic digestion process is strongly affected by a number of environmental factors, each of which is discussed in detail below.

Metabolic process

Anaerobic digestion of biodegradable wastes involves a large spectrum of bacteria of which three main groups are distinguishable.

1. The first group comprises the fermenting bacteria which perform hydrolysis and acidogenesis. This involves the action of exo-enzymes to hydrolyze polymeric matter like proteins, fats and carbohydrates into smaller units

which can then enter the cells to undergo an oxidation-reduction process resulting in the formation of VFA (volatile fatty acids) as well as some carbon dioxide and hydrogen. Because of their production of VFA, the fermenting bacteria are usually designated as acidifying or acidogenic population.

2. The acetogenic bacteria constitutes the second group of microorganisms and is responsible for breaking down the products of the acidification step to form acetate. In addition, hydrogen and carbon dioxide (in the case of odd numbered carbon compounds) are also produced during acetogenesis.
3. The third group involves the methanogenic bacteria which convert acetate or carbon dioxide and hydrogen into methane. Other possible methanogenic substrates like formate, methanol, carbon monoxide and methylamines are of minor importance in most anaerobic digestion processes.

In addition to the three main groups mentioned above, hydrogen consuming acetogenic bacteria are always present in small numbers in an anaerobic digester. They produce acetate from carbon dioxide and hydrogen and therefore compete for hydrogen with the methanogenic bacteria. Also, the synthesis of propionate from acetate, as well as production of longer chain VFA occurs to a limited extent in anaerobic digestion. Competition for hydrogen can also be expected from sulphate reducing bacteria in the case of sulphate containing wastes (DeZeeuw 1986).

In practice, these various reaction processes proceed simultaneously in the digester. Even in the `two-stage digestion plants' the same microbiological processes take place in the two series-connected reactors in such a manner that only the intensity of the digestion process is higher in the first reactor by reason of the higher concentration of the substrate. Hydrolysis and acid formation are effected by a large group of different facultative anaerobes. This stage therefore exhibits considerable tolerance towards changes in the medium in terms of temperature, pH and toxic impurities. The acetogenic and methane-forming bacteria, are, on the contrary, sensitive specialized organisms and the conditions in the reactor must be adjusted according to their particular requirements (Mudrak and Kunst 1986). Thus, the process design depends upon the particular waste stream to be treated. For instance, the effluent from sugar and starch factories is easily hydrolyzed and converted to acids. In such cases, the methane formation is usually the rate limiting step. If one wishes to optimize the treatment process of an effluent of this kind, then a two stage method suggests itself. When dealing with wastewater which is less easily hydrolyzed such as cellulose-containing effluents, then the rate limiting step is the hydrolysis and acid fermentation. For an effluent of this kind, a two-stage process presents no advantage. The potential benefits of a two stage operation are (DeZeeuw 1986):

1. Process optimization is possible i.e.
    - i. The first stage reactor can be operated at pH 5.5–6.0 which is the optimal pH for carbohydrate acidification (in contrast to a methanogenic reactor which operates at a pH of 7.0–7.5)
    - ii. The high growth rates of acidifying bacteria enable very high conversion rates in the first stage acidogenic reactor which consequently can be much smaller than the methane reactor and
    - iii. Excess acidifying biomass can be wasted without losing the slower growing methanogenic biomass.

2. Process stability is better since
    - i. A proper working acidification reactor prevents overloading of the methane reactor by acidifiable substrates which may otherwise lead to fatal pH drop in poorly buffered systems
    - ii. Some substances that inhibit methanogens can be removed or converted in a first stage reactor and
    - iii. The first stage reactor may act as an equalizing tank.

The drawbacks of a staged process are that instead of one big reactor, two smaller reactors are required. This would entail the need for more control apparatus since in order to maintain optimal environmental conditions in both the reactors, rigorous pH and temperature controls would become imperative.

Temperature

Like all biological processes, anaerobic digestion is strongly influenced by temperature and can be grouped under one of the following categories (Hulshoff 1995) viz. psychrophilic (0–20°C), mesophilic (20–42°C) and thermophilic (42–75°C). The details of the bacterial processes in all the three temperature ranges is well established though a large section of the reported work deals with the mesophilic operation. Changes in temperature are well resisted by anaerobic bacteria, as long they do not exceed the upper limit as defined by the temperature at which the decay rate begins to exceed the growth rate. In the mesophilic range, the bacterial activity and growth decreases by one half for each 10°C drop below 35°C (Hulshoff 1995). Thus, for a given degree of digestion to be attained, the lower the temperature, the longer is the digestion time.

The effect of temperature on the first stage of the digestion process (hydrolysis and acidogenesis) is not very significant, as among the mixed population there are always some bacteria which have their optimum within the range concerned. The second and third stages of decomposition can only be performed by certain specialized microorganisms (acetogenic and methanogenic bacteria) and thus, these are much more sensitive towards temperature change

(Mudrak and Kunst 1986). However, an important characteristic of anaerobic bacteria is their decay rate is very low at temperatures below 15°C. Thus it is possible to preserve the anaerobic sludge for long periods without losing much of its activity. This is especially useful in the anaerobic treatment of wastewater from seasonal industries such as sugar mills.

pH

Anaerobic reactions are highly pH dependent. The optimal pH range for methane producing bacteria is 6.8–7.2 while for acid-forming bacteria, a more acid pH is desirable (Mudrak and Kunst 1986). The pH of an anaerobic system is maintained between methanogenic limits to prevent the predominance of the acid-forming bacteria which may cause VFA accumulation. It is essential that the reactor contents provide enough buffer capacity to neutralize any eventual VFA accumulation, and thus prevent build-up of localized acid zones in the digester. In general, sodium bicarbonate is used for supplementing the alkalinity since it is the only chemical which gently shifts the equilibrium to the desired value without disturbing the physical and chemical balance of the fragile microbial population (Hulshoff 1995).

Nutrients and trace elements

The bacteria in the anaerobic digestion process requires micronutrients and trace elements such as nitrogen, phosphate, sulphur, potassium, calcium, magnesium, iron, nickel, cobalt, zinc, manganese and copper for optimum growth. Although these elements are needed in extremely low concentrations, the lack of these nutrients has an adverse effect upon the microbial growth and performance. Methane forming bacteria have relatively high internal concentrations of iron, nickel and cobalt. These elements may not be present in sufficient concentrations in wastewater streams from the processing of one single agroindustrial product like corn or potatoes or the wastewater derived from condensates. In such cases, the wastewater has to be supplemented with the trace elements prior to treatment (Hulshoff 1995). The required optimum C:N:P ratio for enhanced yield of methane has been reported to be 100:2.5:0.5 (Somayaji 1992).

The minimum concentration of macro- and micronutrients can be calculated based on the biodegradable COD_{BD} (chemical oxygen demand) concentration of the wastewater and its degree of acidification (which determines the cell yield factor). The concentration of nutrients required can be calculated as follows (Hulshoff 1995):

$N_{required} = COD_{BD} \times Y \times N_{bacteria} \times 1.14$

where

COD_{BD}	biodegradable chemical oxygen demand (COD_{BD}) in the influent (mg/litre)
Y	cell yield (g VSS/g COD consumed)
$N_{bacteria}$	nutrient concentration in bacterial cells (g nutrient/g dry bacteria)
1.14	assumed TSS:VSS ratio of bacterial cells
$N_{required}$	minimal nutrient concentration required in influent (mg/litre)

In general, for acidified wastewaters, a Y value of 0.03 is used while for non-acidified wastewaters, Y is taken to be 0.15. Table 8 presents the elemental composition of the methane bacteria. The nutrient concentration in the influent should be adjusted to a value equal to twice the minimal nutrient concentration required to ensure that there is a small excess in the nutrients needed.

Table 8 The elemental composition of methane bacteria

Macronutrients		*Micronutrient*	
Element	*Concentration* (mg/kg)	*Element*	*Concentration* (mg/kg)
N	65,000	Fe	1800
P	15,000	Ni	100
K	10,000	Co	75
S	10,000	Mo	60
Ca	4,000	Zn	60
Mg	3,000	Mn	20
		Cu	10

Source Hulshoff 1995

Toxicity

Toxic compounds are divided into the following categories (Hulshoff 1995):

1. pH related compounds: These are chemicals which cause relatively reversible toxicity at moderate concentrations and are common to many anaerobic treatment systems. These include volatile fatty acids (VFA), ammonia (NH_3), especially where amino acids and proteins are important constituents in the wastewater and hydrogen sulfide (H_2S) for wastewater containing high concentrations of sulphur compounds. The toxicity in all these cases is pH related.

2. Strong toxins: This covers compounds with an immediate, irreversible toxicity at very low concentrations such as many organic solvents and some heavy metals.
3. Phenolic and fatty compounds : These include phenolic compounds (cresols, lignin and related compounds, tannin etc.), fats (in the form of long chain fatty acids) and apolar compounds (resins). The effect varies from strong irreversible toxicity to slowly recoverable toxicity at moderate concentrations.
4. Salts which include cations with relatively reversible toxicity at high concentrations and
5. Oxygen: This is toxic for obligatory anaerobic bacteria like methanogenic bacteria. In practice, the presence of oxygen usually does not cause any problems, except when treating wastewater with very low concentrations of organic pollutants (<0.5 g COD/litre) at very short liquid retention times.

pH toxicity

The toxicity of the common methanogenic inhibitors (VFA, NH_3 and H_2S) is highly influenced by pH. Maintaining a reactor pH which causes a high level of dissociation (i.e high pH for VFA and H_2S and low pH for NH_3) will reduce the toxic effect of these compounds. Other compounds like heavy metals and fatty substances (fat, lignin and resin) have toxicities related to pH but as an indirect effect of solubilization/precipitation reactions. A pH which causes a high level of insolubilization will presumably reduce their toxic effect (i.e. high pH for heavy metals and low pH for fatty substances) (Hulshoff 1995).

Ammonium toxicity

Table 9 presents some data on ammonia toxicity in methanogenic processes (Omil, Mendez and Lema 1995). Nitrates may also exert an inhibitory effect since they may undergo denitrification or ammonification in the anaerobic medium and may thus interfere with methane formation due to a shift in the redox potential.

Table 9 Ammonia toxicity in methanogenic processes

Biomass	*Substrate*	*N-TA*[1](g N/litre)	*N-FA*[2] (g N/litre)	*Inhibition*	*T* (°C)	*pH*
Suspended	C2, C3, C4[3]	3.0	24	NR[4]	30	7.0
Suspended	Piggery manure	NR	125	*	37	NR
Suspended	Cattle manure	6.0	700	**	55	7.5
Suspended	Cattle manure	4.0	390	**	55	7.4
Suspended	Acetate	5.0	55	***	NR	7.0
Suspended	SFPWW[5]	2.8	85	50%	37	7.4
Suspended	C2	4.0	30	50%	30	7.0
Biofilm	Acetate	12.0	85	50%	35	6.8
Granular	Potato juice	4.1	145	50%	30	7.5-7.8

[1] TA - total ammonia
[2] FA- fixed ammonia
[3] C2- acetate; C3- propionate and C4- butyrate
* Inhibition threshold for unadapted sludges
** Inhibition threshold for adapted sludges
***Maximum value achieved without process failure
[4] NR- Not reported
[5] SFPWW- sea-food processing wastewater

Source Omil, Mendez and Lema 1995

Sulphur toxicity

Sulphur can occur in wastewater either in the organic form or inorganic sulphur of various oxidation numbers. In the process of anaerobic wastewater treatment, sulphur compounds are usually converted to sulphide by biological reduction. Sulphide formation leads to problems of odour and corrosion. Sulphide is also toxic for higher organisms and is an inhibiting substance in anaerobic microbial processes. Though the inhibiting effect due to sulphide in anaerobic wastewater treatment is well established, the published values differ considerably. This could be due to one or a combination of the following :

- There are three inhibiting effects of sulphide or sulphide reduction viz. direct toxicity of sulphide, substrate competition between sulphate reducing and methanogenic bacteria and precipitation of trace elements by sulphide (Wieman, Schenk and Hegemann 1998). The direct toxicity in particular, correlates exclusively with the undissociated amount of sulphide as hydrogen sulphide (H_2S) (Mudrack and Kunst 1986). Because the degree of dissociation is dependent on the pH value, it has to be known when sulphide toxicity is quantified.
- Under certain conditions sulphide formation results in a positive effect on the digestion process. As H_2S forms insoluble compounds with heavy metals, a detoxification of heavy metals inputs may ensure, so long as sulphide and heavy metals are present in equivalent proportions in the digester (Mudrak

and Kunst 1986).

It has been observed that sulphide toxicity is lower in suspended growth systems than in anaerobic filters. Hence biofilm or granular flocculent sludges present a more complex system (Omil, Mendez and Lema 1995). Table 10 summarizes the sulphide toxicity in various methanogenic processes.

Table 10 Sulphide toxicity in methanogenic processes

Biomass	*Substrate*	*DS*[1] (mg/litre)	*FS*[2] (mg/litre)	*Inhibition*	*T* (°C)	*pH*
Suspended	Acetate	160	50	50%	30	7.0-7.4
Suspended	DW[3]	390	130	50%	37	7.0—7.2
Suspended	Acetate	295	125	50%	35	6.5-7.4
Suspended	Acetate	1060	100	50%	35	7.7-7.9
Suspended	Lactate	250	100	50%	35	7.0
Suspended	Lactate	1630	100	50%	35	8.0
Suspended	C2, C3[4]	145-195	60-65	*	35	7.0-7.2
Suspended	C2, C3[4]	150-200	60-75	**	35	7.0
Biofilm	Propionate	1000	200	**	35	7.4
Biofilm	Acetate	400	125	NR[5]	35	7.2
Granular	Acetate	676	250	50%	30	6.4-7.2
Granular	Acetate	1045	90	50%	30	7.8-8.0

[1] DS- dissolved sulphide [2] FS - free hydrogen sulphide [3] DW- distillery wastewater

[4] C2- acetate; C3- propionate [5] NR- Not reported

* Process failure; ** Inhibition threshold for adapted sludges

Source Omil, Mendez and Lema 1995

Heavy metals

Industrial wastewater can contain heavy metals such as chromium (in tannery effluent). The presence of heavy metals in the influent can be toxic to the biological processes and can affect the waste degradation. Table 11 summarizes the methanogenic toxicity of some heavy metals. The concentrations given in the table refer to the added heavy metal concentrations responsible for 50% inhibition of methanogenesis in the range of 30 to 300 mg/litre.

Salt Toxicity

Salt in the form of cations can cause toxicity problems if the concentration is very high. Table 12 lists the methanogenic toxicity of various cations for digested domestic sludge at 35°C and 7.0 pH. The values are in terms of 50% inhibitory concentration. The results of this table indicate that monovalent cations like sodium are less toxic than divalent cations like calcium.

Table 11 The methanogenic toxicity of heavy metals

Metal	Conc. (mg/litre)	Substrate	Sludge	Adaption	Reference
Cr^{3+}	>224 (8%)*	C_2	CSTR	no	Mosey, Swanwick, Mughes 1971
Cu^{2+}	≈ 250	H_2	M. formicicum	no	Hobson and Shaw 1976
Zn^{2+}	≈90	C_2	CSTR	no	Mosey, Swanwick, Mughes 1971
Pb^{2+}	≈300	C_2	CSTR	no	Mosey, Swanwick, Mughes 1971
Cd^{2+}	80	C_2	domestic	no	Mosey 1971

* Maximum concentration tested; % inhibition is in parenthesis

Table 12 Methanogenic toxicity of various cations

Salt	Mg^{2+}	Ca^{2+}	K^{+}	Na^{+}
Concentration (mg/litre)	1930	4700	6100	7600

Source Kugelman and McCarty 1965

Design considerations for high rate biomethanation processes

All the modern high rate biomethanation processes are based on the concept of retaining high viable biomass by some mode of bacterial sludge immobilization. These are achieved either by the formation of highly settleable sludge aggregates combined with gas separation and sludge settling or by bacterial attachment to high density particulate carrier materials or entrapment of sludge aggregates between packing material supplied to the reactor. The qualitative description of some high rate biomethanation processes commonly used in India are described in the following sections. Some frequently used terms are defined below.

A. Solid Retention Time

The SRT (solid retention time) is the average retention time of organisms in the system. The SRT is defined as:

$$\text{SRT} = \frac{\text{Volatile Suspended Solids (VSS) in the reactor}}{\text{Volatile solids lost in the effluent/day}}$$

In a biological reactor the organism specific growth rate is equal to the reciprocal of the solids retention time of the system. The specific growth rate of the organism is expressed as :

$$\mu = 1/X \,.\, dX/dt = YK\text{-}K_d$$

where,

μ Specific growth rate of organisms, m^3/m^2 h

X Organisms concentration, kg VSS/m^3

Y	Organisms specific yield coefficient
K	Specific substrate utilization rate, kg COD/kg h
K_d	Organisms decay coefficient, h^{-1}

Thus, $1/SRT = YK - K_d$

B. Organic Volumetric Loading Rate (OVLR)

This parameter is frequently used to illustrate the efficiency of reactors in comparison to other systems in treating wastewater. The OVLR (organic volumetric loading rate) of the system is defined as:

$$OVLR = QS_0/V = S_0/T$$

Where,

Q	Influent flow rate, m^3/d
S_0	Influent substrate concentration kg/ m^3
V	Reactor volume, m^3
T	Reactor hydraulic retention time, d

C. Hydraulic Retention Time

The HRT (hydraulic retention time) is the ratio between the volume and the influent flow rate of the wastewater. In the case of wastewater treatment, the actual design HRT depend on the wastewater organic strength.

D. Recycle Ratio

The recycle ratio is given by the ratio of the influent flow rate and the recycle flow rate. For concentrated wastes, very high degree of recycle is often needed to dilute the organic materials present in high concentration to an acceptable level.

ed film reactor

In stationary fixed film reactors (fig. 2), cells are deliberately attached to large size solid support. The reactor has a biofilm support structure (media) for biomass immobilization, wastewater distribution system for uniform distribution of wastewater above/below the media and effluent draw off and recycle facilities (if required). The fixed film reactors offer distinct advantages such as simplicity of construction, elimination of mechanical mixing, better stability at higher loading rates, and capability to withstand large toxic shock loads (van den Berg, Kennedy and Samson, 1985). In addition, these reactors can tolerate sudden organic shock loads at constant hydraulic loading and recover normal performance within few days, if the alkalinity is sufficiently high to maintain the pH above 6.2 (Kennedy and Droste 1985). The reactors can process different waste streams with little compromise in capacity and can adapt readily to changes in temperature. This is important for installations where wastewater characteristics change rapidly. The reactors can startup very quickly after a period of starvation (one or two days to reach maximum capacity after 3 weeks of starvation) (van den Berg, Kennedy and Samson 1985). The main limitation of this design is that the reactor volume is relatively high compared to other high rate processes due to the volume occupied by the media.

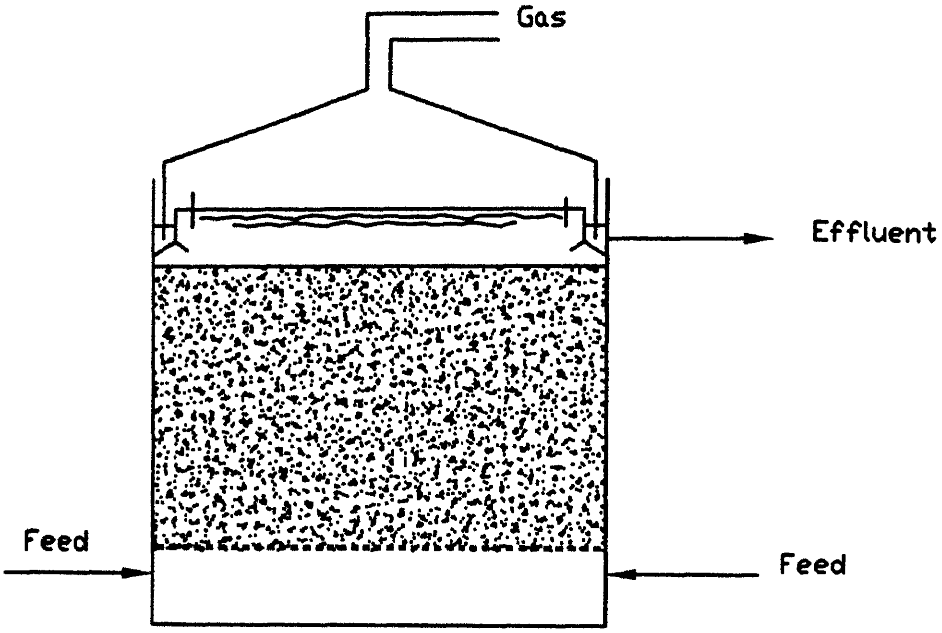


Figure 2 Schematic of fixed film reactor

Another common problem associated with stationary fixed film reactors is clogging due to non-uniform growth of biofilm thickness and/or high suspended solids concentration in the wastewater. Non-uniform growth and consequent clogging occurs especially at the influent entry (van den Berg, Kennedy and Samson 1985). Some measures to combat this problem includes recirculation of effluent and gas for developing a relatively thin film and sloughing of biomass, provision for relatively thin layer of media near the load entering area to accumulate the excess biofilm and improvement in the flow distribution system to avoid very low liquid velocity.

Activated carbon, PVC (polyvinyl chloride) supports, hard rock particles and ceramic rings are the various types of film support which have been tried. Reactor configuration and operation (upflow or downflow mode of operation) have marked effect on performance of the reactor (van den Berg, Kennedy and Samson 1985). With wastes containing large amounts of hard to digest suspended solids recirculation helps to keep these in suspension and aid in their degradation (Kennedy and van den Berg 1982).

Reactor startup and performance

Table 13 provides a list of some start up methods for anaerobic fixed bed reactors. The reactor startup and overall reactor performance depends to a significant extent upon the type of support media. Smooth inert surfaces such as glass and rigid foam PVC have very slow startup and poor performance due to difficulty in attachment of biomass while physical roughening of smooth plastic surface and addition of sawdust to clay support media before filling enhances startup and reactor performance (van den Berg, Kennedy and Samson 1985). The rate of startup depends on several factors such as concentration of critical types of bacteria, properties of the waste as compared to the media used for inoculum preparation(Kennedy and Dorste 1985), the type of inoculum, strength of waste, level of volatile acids, recirculation rate and characteristics of the support material used. The support material as well as the number of channels in a reactor affect the startup and ultimate loading rates (van den Berg, Kennedy and Samson 1985) due to differences in mixing patterns. In addition, the surface to volume ratio of the reactor also influences the reactor performance. It has been found that a higher surface area to volume ratio resulted in increased space loading rates and COD removal (Kennedy and Dorste 1985).

Table 13 Start up of fixed film reactors

Method	*Observations during start up*	*Initial loading* ($kg COD/m^3d$)	*Start up period* (months)
Inoculum mixture of soil, wastewater and manure, 1 month without influent	a. Loading increased 25-100% per week	1	2
	b Start up period depends upon type of inert media		1-3
	c. 4 times faster start up with sludge from identical process than with municipal digester sludge		8-13
Seeded with sludge digester	Without seeding no gas production and biomass accumulation for 1 month	1	1 5

Source Hanze and Harremoes 1982

Basic design parameters

A. Organic volume loading rates

Loading rates and organic removal efficiencies depend upon the type of waste as well as the total amount of active biomass retained in the system. For a wide variety of industrial wastes, loading rates of 5 to 25 kg COD/m^3 d are readily obtained with 70–95% COD removal efficiency depending on loading rate and type of waste (van den Berg, Kennedy and Samson 1985).

B. Temperature

Kennedy and van den Berg (1981) reported the effect of temperature on the performance of fixed film reactors treating chemical industry waste (COD 14 g/litre) and bean blanching waste (COD 10g/litre). The maximum loading rate decreased linearly with temperature. They proposed the following relationships between temperature(T), loading rate and methane production rate :

$$\text{Methane production rate } (m^3/m^3\ d) = 0.167T - 0.692$$

$$\text{Loading rate } (kg\ COD/m^3\ d) = 0.557T - 1.546$$

The coefficients in these relationships presumably depend on the nature of the substrate and type of fixed film support material as well as the support material configuration and surface to volume ratio.

C. Hydraulic retention time (HRT)

Hydraulic retention time in case of fixed film reactors is the ratio between void volume of the reactor and the volumetric flow rate. It has been found that the HRT varies from few hours to number of days depending on the waste characteristics and strength.

D. Performance

Table 14 presents the performance data of anaerobic fixed bed reactors for various substrates.

Table 14 Performance data for anaerobic fixed beds

Wastewater	*Influent COD* (g/litre)	*Loading rate* (kgCOD/m^3d)	*HRT* (days)	*COD removal efficiency* (%)	*Methane yield* (m^3/m^3d)	*Support material*
Bean blanching waste	10	10-18.5	1.0-0.54	87-88	2.8-5.4	Potters Clay
Molasses fermentation waste	10-50	2-12	2.5-5	57-79	1.4-4.8	Raschig ring
Kraft mill evaporator condensate	1.4	2	0.75	80	0.33*	Plastic
Thermal sludge conditioning liquor	12 4	20 6	0.59	67	0.37*	Plastic
Chemical industry waste	14	17.5	0.8d	81	4.9	Potter's Clay
Pear peeling waste	110-140	18.9	5.8	54	3.4	-
Piggery	27-5	39.2	1.0	27	3.8	-
Whey	66	5-20	3.3-13.2d	87-98	3.6	NPP
Water hyacinth	9-11	15-20	0.5	62-65	0.29*	Insulation brick

*m^3/kg COD removal

Source Kaul, Nandy and Trivedy 1997

Upflow Anaerobic Sludge Blanket (UASB) reactor

UASB (upflow anaerobic sludge blanket) technology is being used extensively for a large number of different types of industrial effluents. The system uses sludge granules as a means of achieving high MCRT (mean cell residence time) thereby achieving highly cost effective designs. UASB processes have found a variety of applications in recent years in the treatment of high strength as well as low/medium strength wastewater and a variety of other substrates. The process has been applied to wastewater generated from a wide cross section of industries such as distilleries, food processing units, tanneries etc., in addition to municipal wastewater. A major advantage is that the technology has comparatively less investment requirements when compared to an anaerobic filter or a fluidized bed system. Among notable disadvantages, it has long start-up period, requirement of sufficient amount of granular seed sludge for faster startup and significant wash-out of sludge during the initial phase of the process.

A UASB reactor (fig.3) essentially consists of gas-solids separator (to retain the anaerobic sludge within the reactor), an influent distribution system and effluent draw off facilities. With a sophisticated feed distribution system installed in a UASB reactor, effluent recycle (to fluidize the sludge bed) is not necessary as sufficient contact between wastewater and sludge is guaranteed even at low organic loads (Lettinga 1982).

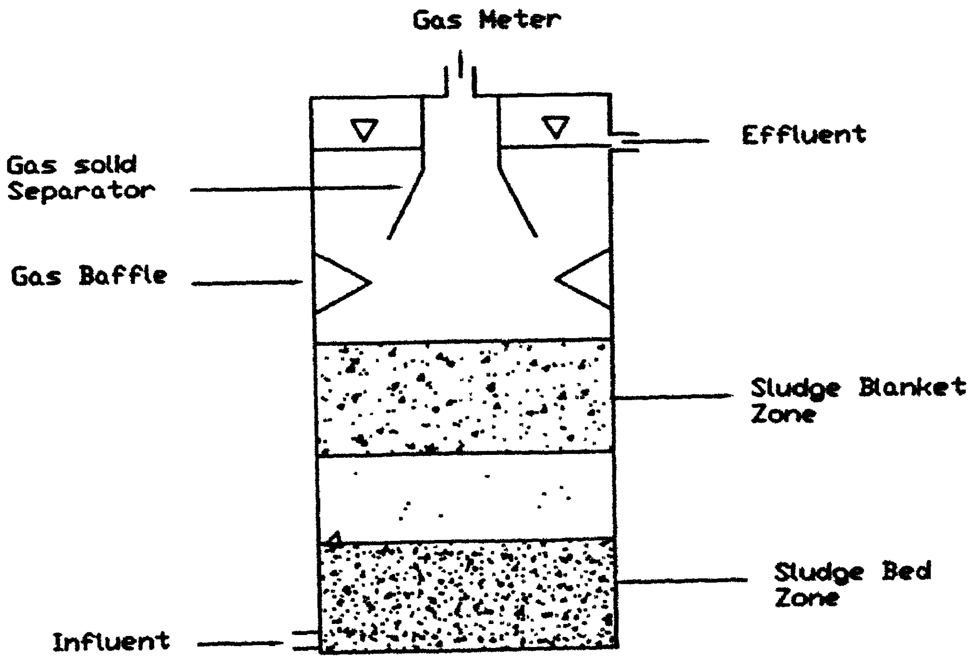


Figure 3 Schematic of UASB reactor

Reactor startup and performance

The driving mechanism of sludge granulation is based on restricting the bacterial growth to a limited number of growth nuclei. This is achieved by operating the reactor appropriately during the start-up phase with suitable type of seed sludge. The reactor startup period is defined as the time after which the sludge characteristics remain unchanged, when treating a wastewater of a constant composition under fixed conditions (DeZeeuw 1986). However, an UASB frequently has two types i.e. granular and flocculent sludges at the end of start-up and the relative amounts of both keeps on changing as a result of growth and selective wash-out. Therefore, the nature of sludge as a whole keeps on changing. A more practical definition used for UASB start-up period is the time required to meet the design criteria of the system. Many authors use the definition of reactor start-up as the time needed to reach a methane production rate of 10 kg CH_4-COD/m^3 d. DeZeeuw (1986) have given the following guidelines for the start-up of UASB reactors with respect to the type and quantity of seed sludge to be used and the start-up conditions to be maintained :

1. Seed sludge
   - i. A concentrated DSS (digested seed sludge) with a concentration of 75 kg/m^3 should be used for low and medium strength wastewater i.e VFA conc. $\leq$ 1 COD/m^3 and 3–6 kg COD/m^3 respectively while a dilute sewage sludge (DSS 30 kg/m^3) should be employed for high strength wastewater (VFA$\geq$10kg COD/m^3).
   - ii. If a concentrated digested sewage sludge is not available, a dilute sludge can be used after unfed storage of this sludge for a prolonged period of time.
   - iii. If no digested sewage sludge is available, digested manure can be used as seed sludge.
   - iv. The rate of reactor start-up can be increased considerably by enriching the seed sludge with a small addition of UASB reactor sludge.
   - v. The quantity of seed sludge should be 10 to 15 kg VSS/m^3 of reactor.

2. Start-up conditions
   - i. To attain a fast start-up the environmental conditions such as pH, temperature and nutrient concentration should be optimal.
   - ii. To avoid sulphide inhibition, sulphide should either be removed first in the influent or its production i.e. the reduction of sulphate, should be simultaneous with methanogenesis.
   - iii. The acetate concentration in the reactor should be kept low enough to allow for growth of both Methanothrix and Methanosarcina. Sludge

granules which consist predominantly of Methanothrix bacteria will not develop if Methanosarcina becomes the dominant acetate converting methanogen. The acetate concentration should not be maintained beyond 1.0 kg/m^3 for prolonged time periods. A step-wise increase in loading rate after reaching a low effluent concentration will ensure the right conditions for the growth of both populations.

iv. When treating a very concentrated wastewater, effluent recycle can be used for dilution. Washed out sludge should not be returned into the reactor, because this adversely interferes with the selection process necessary to develop a sludge with good settleability.

v. Sludge bed erosion wash-out should not be limited by either decreasing the loading rate or by recycling the effluent SS because it is essential for the development of granular sludge from the digested sewage seed sludge. Thus, sludge bed expansion wash-out should also be accepted unless it leads to a decrease in the gas production rate. If the latter occurs, the biomass growth no longer compensates for the loss of active biomass and the system becomes unstable. Temporarily decreasing the loading rate will limit the sludge wash-out in this instance.

It has been observed that in an UASB, a fairly efficient removal of suspended solids (SS)can be accomplished from a very low strength partially soluble wastewater like domestic sewage. For medium strength wastewater, the SS removal efficiency drops down significantly when applying surface loads in the range of 1 m/h, mainly due to the significantly higher gas production, and consequently higher liquid turbulence in the system under these conditions (Lettinga 1985). The UASB reactor is also well suited to the treatment of wastewater with a high sulphide content since the high sludge retention time makes it relatively insensitive to inhibition by sulphide. For instance, it has been observed by Lettinga (1982) in UASB reactors treating yeast production waste that loading rates up to 14 kgCOD/m^3 d could be applied at hydrogen sulphide concentrations of approximately 90 mg/litre. COD removal efficiency of 60–80% was obtained in these cases.

Basic design parameters

A. Gas-solids separator

The gas-solids separator (GSS) separates the gas bubbles from the system below the effluent weir and thereby creates a quiescent zone in the upper part where sludge floc or particles can flocculate, settle out and/or can be entrapped in the sludge blanket present. The broad objectives of the GSS-device in the UASB are:

- Separation and discharge of biogas from the reactor

- Prevention of wash-out of viable bacterial matter
- To enable the viable sludge to slide back into the digester
- To provide a polishing effect and
- Prevention of washout of floating granular sludge.

Lettinga and Hulshoff (1986) have provided some guidelines for the design of GSS system. The slope of the settler bottom should be between 45–60 degrees. The gas collector should be between 1.5–2 m at reactor heights of 5–7 m, with the surface area of the apertures between the gas collectors being 15–20% of the reactor surface area. A liquid gas interface should be maintained in the gas collector in order to facilitate the release and collection of gas bubbles and to combat scum layer formation. Generally scum layer baffles should be installed in front of the effluent weirs. Also, in order to avoid upward flowing gas bubbles to enter the settler compartment, the overlap of the baffles installed beneath the apertures should be 10–20 cm. Antifoam spraynozzles should be installed in the upper part of the gascap in case the treatment is accompanied by heavy foaming. Lastly, the gas exhaust pipes should be sufficiently large to guarantee easy removal of biogas from the gas collection cap.

In applying very high sludge loads, appropriate adjustments have to be made to the design of the GSS because under these conditions, a considerable fraction of the sludge granules will be redispersed in the liquid medium above the sludge bed due to marked turbulence brought about by rising gas bubbles, as well as the increasing tendency of the granules to float (Lettinga 1984).

B. Feed inlet system

The number of feed inlet points in a UASB should be maximum to reduce short circuiting of the liquid flow. Acceptable results can be achieved in high load processes (i.e. at greater than 1–2 kg COD/m^3d) with one feed inlet point per 5–10 m^2. For low loaded granular sludge and/or dense flocculent sludge bed systems, one feed inlet point per m^2 may be sufficient (Lettinga 1982). Table 15 presents recommendations for the number of feed inlet points required in a UASB reactor with respect to different types of sludge (Lettinga 1985).

Table 15 Rough guidelines for the number of feed-inlet points required in a UASB

Type of sludge	*Area per feed inlet point* (m^2)
Dense flocculent sludge (>40kg TSS/m^3)	0.5-1 at loads < 1 kgCOD/m^3 d
	1-2 at loads 1-2 kgCOD/m^3 d
	2-3 at loads > 2 kgCOD/m^3 d
Medium thick flocculent sludge (20–40kg TSS/m^3)	1-2 at loads < 1-2 kgCOD/m^3 d
	2-5 at loads > 3 kgCOD/m^3 d
Granular sludge	0.5-1 at loads up to 2 kgCOD/m^3 d
	0.5-2 at loads 2-4 kgCOD/m^3 d
	>2 at loads > 4 kgCOD/m^3 d

C. Organic loading rate

Significantly higher loading rates can be accommodated in granular sludge UASB reactors as compared to flocculent sludge bed reactors. It is recognized that the suspended solids reduction in granular sludge bed systems becomes very poor at high loads mainly because of considerable turbulence resulting from vigorous gas evolution. A primary and secondary settler therefore has to be installed in line with the anaerobic reactor(Lettinga 1984).

For partially insoluble wastes, generally low loading rates are applied. In flocculent sludge bed UASB reactors, the presence of poorly degraded or non-biodegradable suspended matter in the wastewater will result in an irreversible sharp drop in the specific methanogenic activity because the dispersed solids will be trapped in the sludge. Moreover, any significant granulation will not occur under these conditions. The maximum loading potential of such a flocculent sludge bed system is in the range of 1–4 kg COD/m^3d (Lettinga 1984).

The maximum achievable loading rate in EGSB (expanded granular sludge blanket system) is slightly higher than that of an UASB system, specially for a low strength VFA containing wastewater and at lower ambient temperatures. EGSB is a modified form of UASB in which a slightly higher superficial liquid velocity is applied (5– 10m/h as compared to 3m/h for soluble wastewater and 1–1.25m/h for partially soluble wastewater in an UASB) (Lettinga 1995). Because of the higher upflow velocities, mainly granular sludge will be retained in an EGSB system, whereas a significant part of granular sludge bed will be in an expanded or possibly even in a fluidized state in the higher regions of the bed. As a result, the contact between the wastewater and sludge is excellent. Moreover, the transport of substrate into the sludge aggregates is much better as compared to situations where the mixing intensity is much lower (Lettinga 1995). Table 16 and 17 present guidelines for permissible daily average loading rates for UASB systems treating wastewater of different strengths.

Table 16 Permissible loading rates for UASB and EGSB reactors (average granular sludge concentration of 25 kg VSS/m^3)

	Design-capacity (kg/m^3 d)			
	UASB	*EGSB*	*UASB*	*EGSB*
Temperature(°C)	*VFA wastewater*		*non-acidified wastewater*	
10	1-2	4-8	0.5-1.5	2-5
15	2-4	6–10	1.5-3	4-7
20	4-6	7-13	2-4	5-9
25	6-12	9-15	4-8	7-11
30	10-18	12-20	8-12	9-14
35	15-24	15-25	12-18	12-18
40	20-32	20-32	15-24	15-24

Table 17 Applicable space loads for granular sludge and flocculent sludge UASB reactors

		Applicable loading rates at 30°C (kg COD/m^3 d)		
		Granular sludge UASB	*Flocculent sludge UASB*	
Strength of waste (mg COD/litre)	*Fraction insoluble COD* (%)		*Low TSS removal*	*High TSS removal*
up to 2000	10-30	2-4	8-12	2-4
	30 to 60	2-4	8-14	2-4
	60 to 100	*	*	*
2000-6000	10 to 30	3-5	12-18	3-5
	30 to 60	4-6	12-24	2-6
	60 to 100	4-8	*	2-6
6000 - 9000	10 to 30	4-6	15-20	4-6
	30 to 60	5-7	15-24	3-7
	60 to 100	6-8	*	3-8
9000-18000	10 to 30	5-8	15-24	4-6
	30 to 60	Doubtful at TSS > 6-8 g/litre	Doubtful at TSS > 6-8 g/litre	3-7
	60 to 100	*	*	3-7

* UASB process not applicable under these conditions

Source Lettinga 1985

D. Sludge bed height

Experiments carried out in a 6 m^3 pilot plant in which a dense granular sludge bed occupied the lower 1–2 m of the reactor (with a more flocculent sludge blanket above it) have shown that space loads upto 45 kg COD/ m^3 d with potato processing waste and 30 kg COD/m^3 d with sugar beet waste can be well accommodated (Lettinga 1982). However, there is no fixed criteria for the total amount of granular sludge to be retained in an UASB reactor.

E. Performance

UASB reactors have been used for a wide variety of substrates at optimal and suboptimal mesophilic temperatures. Table 18 presents the performance data for upflow anaerobic sludge blanket reactor with various types of substrates.

Table 18 Performance data for upflow anaerobic sludge blanket reactor with various substrates

Wastewater	*Influent COD* (g/litre)	*Loading rate* (kg COD/m^3 d)	*HRT* (h)	*COD removal efficiency* (%)	*Methane yield* (m^3/m^3d)
Bean blanching waste	10	14.20	-	86 93	4-8
Chemical industry waste	14	61-18	-	80-82	4-5
Thermal sludge conditioning liquor	12.4	5.9	49	71	0 4*
Beet sugar wastewater	10-50	15	24	80-98	0.35-0.56*
Dairy waste	4	5-15	6.5-19	62-92	1-3 0 32*

* m^3/kg COD removed

Source Kaul, Nandy and Trivedy 1997

Anaerobic fluidized bed treatment

In the anaerobic fluidized bed (fig. 4), the media for bacterial attachment and growth is kept in the fluidized state through application of high upflow velocities normally achieved by recycling the effluent. Increasing recycle allows the process to tend towards the operational characteristics of a completely mixed system. The design of a fluidized bed thus consists of a wastewater distributor, a media support structure, media, head space, effluent draw off and recycle facilities. The thickness of the biofilm is controlled by the bed regeneration and by the size and density of the inert media in combination with the upflow velocity. Excess sludge can be removed from the top of the fluidized bed where the biofilm tends to have the maximum thickness.

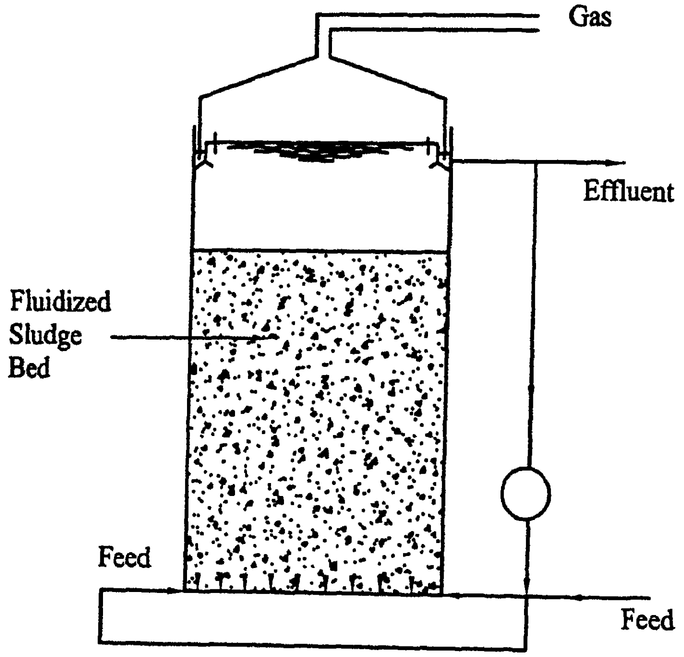


Figure 4 Schematic of anerobic fluidized bed system

Fluidized bed technology is more effective than anaerobic filter technology as it favours the transport of microbial cells from the bulk to the surface and thus enhances the contact between the microorganisms and the substrate (Perez, Romero and Sales 1998). These reactors have several advantages over anaerobic filters. They are less likely clog and have a low hydraulic head loss combined with better hydraulic circulation (Collivingnarelli 1991). They are able to operate at lower required retention times and/or higher loading rates (Perez , Romero and Sales 1998) and have a greater surface area per unit of reactor volume. Finally, the capital cost is lower due to reduced reactor volumes. However, the recycling of effluent may be necessary to achieve bed expansion. Thus, the stationary packed bed technology is adequate for the treatment of easily biodegradable wastewater or where high COD removal is not required, while the fluidized bed technology is especially suitable for treatment of hazardous wastes with recalcitrant compositions (Perez, Romero and Sales 1998).

Basic design parameters

Table 19 gives the typical design parameters for anaerobic fluidized bed and expanded bed reactors.

Table 19 Basic design and operation parameters for anaerobic fluidized bed reactors

Parameter	*Expanded Bed*	*Fluidized Bed*
Inert material type	Garnet/Sand/Carbon	Sand/Garnet/Carbon
Inert material diameter, mm	0.3-3	0.2-1
Inert materials submergence, %	100	100
Bed expansion, %	20-40	30-100
Specific surface area, m^2/m^3	1000-3000	1000-2500
Height of reactor, m	2-4	4-8
Radius of reactor, m	2-3	2-3
Vertical velocity, empty bed (incl recycle) m/h	2-10	6-20
Recycle ratio	2-100	5-500
Biomass concentration, kg SS/m^3	10-30	10-20
Attached biomass, % of total	90-100	95-100
Suspended biomass, % of total	0-10	0-5
Effluent SS, gm/m^3	20-100	20-100
Gasflux, vertical, Nm^3/m^2d	5-40	5-40
Gasflux, vertical maximal, Nm^3/m^2d	30-40	30-40
Energy pumping, Whr/m^3	10-20	15-30
Energy pumping, Whr/m^3 (incl recycle)	20-1000	75-3000

Source Kaul and Nandy 1998

Filter Media. The filter media for a fluidized bed should be able to provide a large specific surface area and be easy to fluidize. The medium used for biofilm attachment are small diameter inert particles such as sand, anthracite or granular activated carbon. Specialized supports such as 'Biotite' have also been recommended (Ehlinger, Audic and Faup 1989). There are trade-offs between size and density of particles and stability of operation with these systems. Smaller particles provide greater specific surface area-to-volume ratio and thus provide greater surfaces for attached biofilms. In addition, lighter particles can be fluidized at lower upflow velocities which reduce the recycle rate necessary to achieve a given HRT.

Inlet distribution system. The correct design of the inlet distribution system is a key aspect of the fluidized bed reactor (Iza 1991). Holst, Truc and Pujol (1997) recommend a grid consisting of one or more manifolds including ramification pipes that have distribution holes facing downward. The size of the holes must be small enough to evenly distribute the flow but must also be large enough to avoid clogging.

Triple-phase separation. The separation zone for the different phases viz. gas phase (biogas), liquid phase (treated water + recirculation stream) and the solid phase (media particles and suspended solids) is located above the reaction zone. The triple-phase separator consists of an internal cylinder mounted above a sedimentation cone and acts as a syphoid, creating a tranquilizing area. The transition between the reaction zone and the separation zone is made through transfer tubes. The flow velocity undergoes acceleration in these tubes and provokes a coalescence of gas bubbles along with separation of the media particles and the suspended solids. The transfer tubes pass through the cone and open up outside of the internal cylinder, just above the water level, in order to avoid foaming problems. The gas collects at the top of the reactor, the liquid and solid phases pass through the syphoid and the settleable material collects in the cone from where it is pumped back into the reaction zone. The treated water flows out through a weir and the recirculation flow leaves through a central water chamber (Holst, Truc and Pujol 1997).

Pretreatment. An efficient pretreatment to remove suspended solids and grease is necessary in order to ensure process stability. The concentration of SS entering the fluidized bed should be less than 500 mg/litre. High concentrations of SS can cause serious damage to the hydraulic functioning of the system due to clogging of the distribution system or heat exchanger (Oliva, Jacquart and Prevot 1989).

Performance. The anaerobic expanded bed process has been demonstrated to be effective for treating low strength waste (COD < 600 mg/litre) at short retention times spanning several hours and at high organic loading rates up to 8 kg COD/m^3 day even at low temperatures (Jewel and Switzenbaum 1980). Table 20 gives the performance data for anaerobic expanded/fluidized beds with various substrates and Table 21 collates the results for some industrial applications.

Table 20 Performance data for anaerobic expanded/fluidized beds

Wastewater	*Influent COD* (g/litre)	*Loading rate* (kg COD/m^{3}d)	*HRT* (h)	*COD removal efficiency* (%)	*Methane yield* (m^3/kg COD removed)
Food processing waste	7-10	3.5-24.1	7.5-49.4	75-86	0.4
Chemical industry waste	12	3.5-5.7	0.6-2.8	79-83	0.41
Kraft mill evaporator condensate	0.42	13	0.8	80	0.14-0.24
Thermal sludge conditioning liquor	12.4	21.7	13.3	50	0.31
Sweet whey	10	8.9-60	4.1-27.1	36.9-93.1	0.16-0.32
Sewage	0.186	0.65-35	0.08-8	81	-

Source Kaul, Nandy and Trivedy 1997

Waste type	Influent (g/litre)	Effluent (g/litre)	Removal (%)	Loading rate (kg/m^{3}d)	HRT	Temperature (°C)	Remarks
Acid whey	50.3-56.1 (COD)	8.3-14.6 (COD)	72.0-83.6	13.4-37.6	1.4-4.9(a)day	35	one stage fluidized bed
Acid whey	52.2-55.4 (COD)	15.1-19.2 (COD)	65.2-71.4	15.0-36.6	1.5-3.5(a)day	24	one stage fluidized bed
Acid whey	52.2 (COD)	3.2 (COD)	94	10.5	5.0day(a)	-	Two stage in series
Food processing	7.2-9.4 (COD)	1.0-1.9 (COD)	75-86	3.5-24.1	7.5-49.4(a)h	35	Fluidized bed
Chemical waste	12 (COD)	-	79-93 (COD)	4.1-27.3	-	35	Fluidized bed
	8.4 (BOD)(b)	-	81-98 (BOD)				
Soft drink bottling	6 (COD)(b)	-	66-89 (COD)	4-18.5	-	35	Fluidized bed
	3.9 (BOD)(b)		61-95 (BOD)				
Heat treatment liquor	10 (COD)(b) 5 (BOD)	-	52-75 (COD) 66-95.5 (BOD)	4.3-21.4	-	35	Fluidized bed
Whey permeate	6.8 (COD)	2.2 (COD)	68 (COD)	8.6-10.4	-	30-35	Fluidized bed
Whey permeate	27.3 (COD)	5 (COD)	82 (COD)	5.3-7.4	-	30-35	Fluidized bed
Sweet whey	10 (COD)	1374-6071 mg/litre (S-COD)	36.9-93.1	8.6-60 0	4.1-27.1(h)(c)	25	Expanded bed
	5-20 (S-COD)	417-7958 mg/litre (S-COD)	58.9-92.3	8.2-29.1	15-35(h)(c)	35	Expanded bed
Black liquor condensate	1.4 (COD)	0.16 (COD)	89	10	3.5(h)	22	Expanded bed
Black liquor	1.4 (COD)	0.28 (COD)	80	13	0.8(h)	22	Fluidized bed

a)Empty bed retention time b)Average values c)Based on expanded bed volume

Source Kaul 1992

Rotating Biological Contactor

The RBC (rotating biological contactor) (fig.5) consists of a series of circular plates mounted over a slowly rotating shaft. The biological growth develops over the plates. The major components of this digester are the central shaft, shaft bearings, media support structures and covers. The RBC is characterized by the following features :

- Adequate cell retention in the reactor and development of long MCRT(mean cell retention time)
- Complete mixing with even distribution of nutrients
- Elimination of the problem of channeling
- Necessity of recycling to overcome pH variations and
- Frequent maintenance of mechanical units.

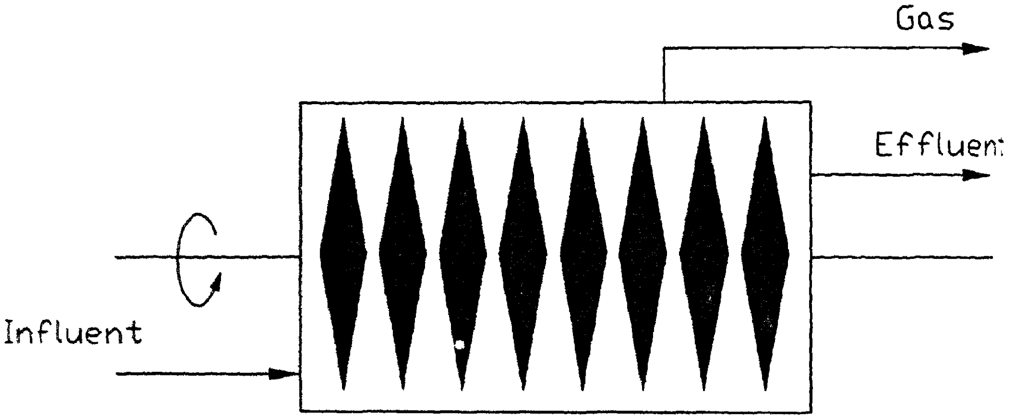


Figure 5 Schematic of rotating biological contactor

The choice of the shaft is an important aspect of RBC design. Though the shaft rotates at a slow speed (1- 2 rpm), it undergoes constant reversing stresses and therefore the size, thickness and section modulus of the shaft must be suitably chosen. Also, the design and workmanship of the welds on the shaft should be of very high quality and the manufacturer should test all shafts by X-ray and ultrasound techniques. The other factors which should be considered are the reliability and efficiency of drive system, ability to dismantle and remove the shafts and an appropriate means of monitoring shaft loads.

The tank geometry should be capable of maintaining minimum scour velocities to limit the settling of suspended solids. Flow distribution in the tank (normally done through fixed weirs) should be uniform to prevent overloading and underloading of the trains. Thus, a provision of flow measurement and control is essential. Also, to prevent overloading and underloading of the trains, RBC effluent is recycled particularly in instances where there is large diurnal flow/strength variation or the capacity of the equalization tank is inadequate.

The performance analysis of the RBC is similar to that of trickling filters. Designing of the RBC is based on the loading factor, geometry of the tankage, hydraulic regime through the system and control of solids build-up. The hydraulic and organic loading rates are crucial for the design of the secondary treatment units. In addition, the structural integrity of the media and microbial attachment are also critical factors.

Hybrid reactor

The hybrid reactor (fig. 6) is an improved version of the UASB system and combines the merits of the upflow sludge blanket and fixed film reactors. This reactor offers strong resistance to disturbances such as large fluctuations in loading rate. As most of the microbes adhere firmly, any change in fermentation conditions would only temporarily affect the microbes. Even at a very high upflow velocity of effluent, the biofilm is not washed away.

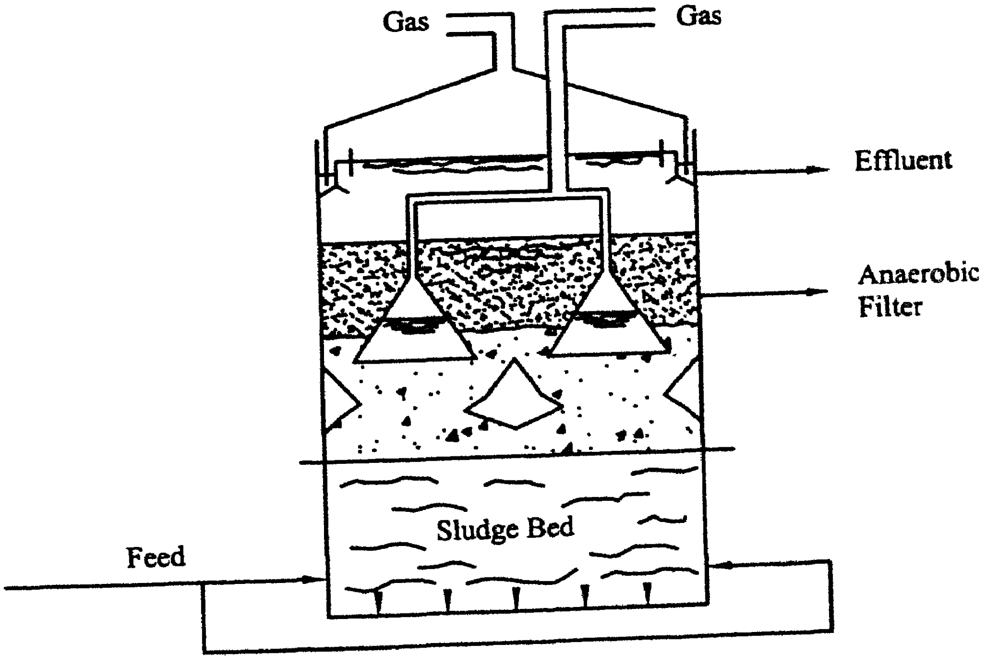


Figure 6. Schematic of hybrid reactor

A successful phase separation (in terms of acidogenic and methanogenic phases) can be achieved with this type of design. Thus, not only does the hybrid reactor provide the best environment for the growth of both the organisms (acidogens and methanogens), it also overcomes the limitations normally experienced with the UASB system.

The hybrid reactor can be used for a wide variety of industrial effluents and it is possible to maintain the desired pH conditions for both the acidogens and the methanogens. The inert matrix material increases the retention of the granular sludge and prevents the washout of the microbial population. By choosing a suitable highly porous packing material with a large specific surface, the adhesion of microbes can be greatly improved and the concentration of activated sludge in the reactors can be considerably enhanced. The rate of mass transfer is also higher owing to the increased contact time between the feed and the microbes. As the material which immobilizes the microbes can capture most of the sludge when the slurry passes through the reactor, the loss of sludge is minimized. Apart from the advantages of simplicity in operation and design, the hybrid reactor also works out to be more economical as compared to fixed bed system at the industrial scale. Table 22 summarizes the typical design features for a hybrid reactor used for distillery effluent.

Table 22 Design and operating features of hybrid reactor

Design Features	
Material of construction	*Mild steel*
Working volume	7700 m^3
HRT	9-10 days
Feed distribution	Through nozzles
Width of packing	5-10% of reactor volume
COD loading	9-11 kg/m^3 per day
Mode of recirculation	Mechanical
Operating Features	
Temperature	37 ± 2°C
pH	7.5-7.7
VFA	2000-5000 mg/l
Digester productivity	3 10 m^3 gas/m^3 reactor per day

Source Bardiya, Hashia and Chandna 1995

Though a wide variety of industrial effluents have been treated using various high rate biomethanation processes (Fang and Chui, 1993; Wiegant and Lettinga, 1985; Canovas-Diaz and Howell, 1988), very limited work has been done on the utilization of hybrid reactor on a large scale. A 14.751 hybrid UASB reactor has been used to treat swine wastewaters (Liao and Ciao, 1994). In this particular case, a rope matrix has been used as a fixed film medium in its mid-section. The additional biofilm attached onto the ropes increased the stability of the reactor and helped maintain steady methane production. Maximum methane production of 0.71 lCH_4/l reactor per day could be achieved at an HRT of 3.3 days and an OLR of 3.5 g COD/l reactor day. The corresponding COD reduction was 57%. In the studies carried out by Cho, Park and Chang (1995) on the degradation of food wastes, a two phase system was used with a hybrid methanogenic reactor. The upper half of this reactor was packed with polyethylene support media and the remaining portion served as a sludge bed. The efficiency of packing material in retaining the biomass has also been established in the treatment of sugarwaste by upflow anaerobic reactor of 4.25 L volume in which plastic rings were used as filter (Guiot and Van den Berg, 1985). Even with severe hydraulic conditions, the accumulated biomass was very high compared to that in a UASB. A maximum methane production rates of 7 m^3/m^3d was achieved. A two stage upflow hybrid reactor (Joubert, Britz and Lategan, 1985) has also been used for treating a synthetic sucrose substrate. In this study, both the acidogenic and methanogenic reactors were provided with polyethylene foam as fixed film material. The pore size of the packing material plays an important role in a hybrid UASB. Viturtia and coworkers in their work on 2-phase anaerobic digestion have compared the effect of two different polyurethane supports of 80 ppi and 15 ppi (Viturtia, Mata-Alvarez, Cechi et al., 1989). The advantage of using a packing material is reflected on the gas production rates as demonstrated in the comparative studies carried out by Dong Shusheng (Shusheng, 1992). A hybrid reactor of 1050 m^3 capacity has recently been installed at Daurala sugar works, Daurala, India, for the biomethanation of distillery effluent (Bardiya, Hashia and Chandna, 1995). It is a 2-phase system with two different reactors for acidogenic and methanogenic digestion. A maximum COD reduction of 70% at a loading rate of 9-11 kg/m^3 d was achieved. The BOD reduction was 83% and 33-35 m^3 of biogas/m^3 of effluent was produced. The study of the reactor performance at various loading rates indicates that the biogas production and the BOD removal (%) are practically unchanged up to 10 kg COD/m^3 day (Table 23). A further increase in the loading rates displays a small decline both in the gas production as well as the BOD reduction.

Table 23 Performance of reactor at various loading rates

Loading Rate	Feed	Biogas		VSS	BOD Removal
(kg COD/m³ day)	(m³/m³)	Methane (%)	H_2S (ppm)	(kg/m³)	(%)
1.0	28-29	65	10-12	1.07	85
2.0	28-29	65	10-15	1.32	86
3.0	29-30	65	10-15	1.76	86
4.0	30-32	65	10-15	1.88	85
5.0	33-35	65	15-20	2.52	85
60.	33-35	65	15-20	2.52	85
7.0	34-35	65	15-20	4.40	84
8.0	34-35	65	15-20	5.75	84
9.0	34-35	63	15-20	5.75	84
10.0	35-36	63	25-28	6.93	84
11.0	32-34	60	28-33	6.85	80
12.0	29-30	58	33-38	6-64	78

Source Bardiya, Hashia and Chandna 1995

Comparative evaluation of high rate anaerobic processes

A new technology is acceptable to an industry if it requires less capital, less land area and is more reliable when compared to the other well established options. For an anaerobic digestion system, this translates into the process being able to run at high organic and hydraulic loading rates with minimum operation and maintenance requirements. All the high rate anaerobic reactors such as UASB, fluidized bed reactors etc. have proved their applicability for a wide spectrum of wastewater over a range of organic loading rates. However, there is considerable overlap in the reported values regarding the performance data for different reactor types since the process is sensitive to environmental conditions. Thus, to choose the most appropriate reactor type for a particular application, it is essential to conduct a systematic evaluation of different reactor configurations with the wastewater stream. In the absence of such data, high rate reactors are compared here with the basic understanding of the process involved. It should however be stressed that this only provides general guidelines for the choice of the reactor and the decision still needs to be validated through experiments.

Organic and hydraulic loading potential

The organic and hydraulic loading potential of a reactor depends on three factors viz. a) amount of active biomass that can be retained by a reactor per unit volume b) contact opportunity between the retained biomass and the incoming wastewater and c) diffusion of substrate within the biomass. With these considerations, granular sludge UASB reactor stands out distinctively as the best choice with the only limitations being the tendency of granules to float and shearing of granules at high loading rates. These constraints are also valid to a lesser degree for attached biomass reactors (such as fixed film, fluidized bed and rotary biological contactors). In addition, due to the space occupied by the media, the attached biomass reactors possess comparatively lower capacity for biomass retention per unit volume of the reactor. The latter depends on the film thickness which would be the highest in a fluidized bed reactor due to large surface area available for biomass attachment. Also, there is better contact between the biomass and the incoming wastewater in both fluidized bed and EGSB systems. However, due to the high upflow velocity, the substrate diffusion in the biomass is limited in these configurations.

Based on these factors, it appears that the maximum achievable loading rates with soluble wastewater would decrease in the following sequence : UASB> EGSB >Fluidized bed reactor > Anaerobic filter, RBC. The capital cost of the reactors and the land area requirements therefore increases in the same order.

Operation and maintenance requirements

The digester operation and maintenance requirements are minimum if the process is fairly stable towards fluctuations in wastewater characteristics and changes in environmental conditions. Susceptibility of the process depends on the potential utilization of the reactor and thus a system operating near maximum loading conditions is more sensitive. Recently, Kaul and Nandy (1998) have qualitatively compared various reactor types (Table 24) and provided the guidelines for reactor choice.

Table 24 Comparison between the various types of reactors

Important parameter	Fixed bed	Expanded bed	Fluidized bed	Sludge blanket
Biofilm structure of microorganism, important	partially	yes	yes	partially
Non-attached biomass, important	partially	no	no	yes
Biofilm thickness control in reactor	no	partially	yes	no
Recycle necessary	no	yes	yes	no
Mixing necessary[3]	no	no	no	partially
Separation equipment necessary	no	no	no	yes
Phasing[1] possible	partially[2]	yes	yes	partially[2]
Suitable for wastes with suspended organic	partially	no	no	partially
Run-through of inerts in raw waste	no	partially	yes	partially
Problems with foaming	no	yes	yes	yes
Problems with gas bubbles in reactor	partially	partially	partially	partially
High microorganism/wastewater contact	no	yes	yes	partially
Tolerates hydraulic overloading	yes	yes	yes	partially
Tolerates organic overloading	yes	partially	partially	partially
Suitable for high concentration of biodegradable toxics	yes[2]	partially	partially	partially[2]
Susceptability to shock-dose toxicants	no	yes	yes	yes
Start up problems	partially	yes	yes	yes
Re-start-up easy	yes	partially	partially	yes

[1] Two reactors with separate acid and gas phases resp. [2] recycle or mixing mandatory

[3] In excess of the mixing caused by gas bubbles

Source Kaul and Nandy 1998

Based on the above table as well as our observations, the following rating can be employed while choosing a reactor type for a particular application.

Parameters	Rating
Operating skills	fixed film< UASB < RBC < fluidized bed
Energy consumption	UASB < fixed film < EGSB < fluidized bed < RBC
Capital cost, land requirement	UASB< EGSB <Fluidized bed reactor < Anaerobic filter, RBC

4 Application of anaerobic processes in Indian industry

India has a significant potential for the implementation of anaerobic digestion in the industrial sector. As discussed earlier in chapter 3, any wastewater which is rich in biodegradable organic matter with adequate nutrients and absence of toxic compounds is suitable for anaerobic treatment. The wastewater satisfying these criteria can either be treated directly by anaerobic process or else after appropriate pretreatment.

Some of the major industries which are suitable for the implementation of anaerobic technology are agrobased operations (distilleries, sugar, dairy, edible oil, coffee pulping and pulp & paper mills), tanneries, textile mills and slaughterhouses.

In order to get first hand information, questionnaires were sent to a number of industries in the above mentioned sectors. The aim of this survey was to collect data on the following :

- Description of the manufacturing process
- Raw materials used
- Sources of wastewater generation
- Wastewater generation rate per unit of production
- Wastewater characteristics
- Details of treatment plant and
- Plant performance

A sample of the questionnaire is given in Annexure III. In addition, modified questionnaires (Annexure IV) were sent to a number of Indian consulting firms involved in turnkey execution of anaerobic digestion technology in the Indian industry. These organizations were requested to provide details of the design and performance of the systems installed by them. They were also asked to comment upon the challenges associated with the adoption of anaerobic technology as well as the identification of specific research activities that needs to be undertaken in this context. Finally, a visit was made to the Pudumjee Paper Mills, Pune to study their anaerobic treatment plant which has been in operation for the past 10 years.

In response to over 300 questionnaires, a total of 27 replies were received according to the following break-up:

Pulp and paper	7
Starch	1
Sugar	4
Textile	7
Edible oil	2
Distillery	3
Slaughterhouse	1
Consultants	2
Total	***27***

Since the response was poor and did not cover all the sectors, some information was also obtained from relevant publications. The results are analyzed sectorwise in the following sections.

Distilleries

There are about 218 large and medium scale distilleries in India. Of these, about 50% of the units are yet to attain satisfactory performance levels with regard to installation and operation of effluent treatment plants (CPCB 1997). Alcohol manufacture in Indian distilleries is based either on molasses or malt-barley. The product range includes industrial alcohol, rectified spirit, pure alcohol and beverage alcohol. The main process includes dilution of molasses with water followed by its fermentation with cultured and developed yeast. The fermented solution is called wash and contains 6 to 8% alcohol. The ferment wash is distilled (with low pressure steam) to separate alcohol. Rectified spirit or neutral alcohol is obtained as the final product. The residue of the distillation process is the spent wash which is a strong organic effluent. The other wastes from the process include yeast sludge (which is usually mixed with spent wash), floor washes, waste cooling water and waste from the operations of yeast recovery or by-products recoveries processes. The characteristics of the composite distillery effluent are as follows:

Wastewater generation	12–16 litre/litre of alcohol production
Temperature	70 to 95°C
pH	4.0 to 5.5
Colour	dark brown
COD	90,000–1,10,000 mg/litre
BOD	35,000–50,000 mg/litre
Total solids	80000–1,20,000 mg/litre
Volatile solids	4000–9000 mg/litre
Nitrogen	900–1000 mg/litre
Phosphorus	40–50 mg/litre
Sulphate	High

The very high organic content in the wastewater makes it unsuitable for direct aerobic treatment and therefore a two stage biological treatment consisting of anaerobic followed by aerobic treatment is usually adopted. While none of the respondents divulged significant design details of the anaerobic plant, COD reduction in most of these is of the order of 70% with gas yield of 0.5 Nm^3/kg of COD destroyed. One respondent quoted that even after having two stage treatment, effluent needs to be diluted to meet the discharge standards.

Various high rate anaerobic reactor designs have been tried at pilot and full scale operation. These are hybrid reactor (Bardiya, Hashia and Chandna 1995), fixed film (Manihar 1995), UASB (Libin, Xiangqiang, Yibo et al. 1997) and continuous stirred reactor (questionnaire survey). However, to make the anaerobic treatment process viable, the effluent needs pretreatment for pH and temperature correction and lime scrubbing of biogas for H_2S removal (if the biogas is to be used for power generation).

A 15–16 MLD diphasic anaerobic plant based on hybrid reactor system has been installed at Daurala Sugar Works, Daurala (U.P) (Bardiya, Hashia and Chandna 1995). The acid phase digester is designed for 34–36 h HRT with COD loading rate of 48–50 kg/m^3 d while the methane phase reactor has a HRT of 9–10 days with a COD loading rate of 9–11 kg/m^3 d. A COD reduction of about 70%, with a biogas production rate of 33–35 m^3/m^3 of effluent with a methane content of 63–65% has been reported.

Manihar (1995) conducted pilot studies on a 100 litre fixed film reactor with varying COD loading in order to optimize the treatment efficiency and methane production. The unit consisted of separate reactors for acidification followed by biomethanation. The 20 litre acidification reactor was constantly agitated and operated at a HRT of 2.5 days to obtain a COD reduction of 10–15%. The fixed film methane reactor consisted of a 100 litre fixed bed filled with random PVC rings having a void volume of 97% and surface area of 320 m^2/m^3. The reactor was operated in the upflow mode with a varying recirculation rate of 15–25 times the inlet effluent rate. The maximum COD loading rate achieved was 25 kg COD/m^3d with an overall COD reduction of 60–70%. The gas yield was 0.4 m^3/kg COD reduction with a methane content of 60–70%.

Experiments on an UASB reactor system conducted by Libin and coworkers (1997) showed a COD reduction of 92%. The unit was operated at 35 C with a HRT of 2.5 days and a COD loading rate of 8.9 g/litre d. Under these conditions, the volumetric gas production rate was 3.2 g/litre d with a methane content of 63%.

The continuous stirred tank reactors (CSTR) installed by one of the respondents has a design HRT of 15–18 days which could bring about a 70% reduction in COD with a gas yield of 0.5 Nm^3/kg COD degraded. Based on this typical figure, it is estimated that distilleries have the potential to generate 0.27

kg LPG equivalent energy from wastewater per liter of alcohol production. Table 25 shows statewise energy generation figures from the anaerobic digestion of distillery wastewater. The energy potential is calculated on the basis of LPG equivalent, with the calorific value of LPG being taken as 10,800 kcal/kg. At the all India level, about 0.32 million tonne LPG equivalent energy could be generated if all distilleries opt for anaerobic treatment of wastewater.

Table 25 Energy generation potential of distillery wastewater (all production figures for the year 1992-93)

State	*Production*[1] (Million litre)	*Energy potential* (tonne LPG)
Andhra Pradesh	86.88	23457
Bihar	31.5	8505
Goa, Daman & Diu	8.23	2222
Gujarat	67.5	18225
Haryana	34	9180
Himachal Pradesh	1.1	297
Karnataka	88	23760
Maharashatra	290	78300
Nagaland	0.8	216
Orissa	3.62	977
Pondicherry	7.6	2052
Punjab	38.34	10351.8
Rajasthan	8.8	2376
Tamil Nadu	80	21600
Uttar Pradesh	431.55	116518.5
All India	1177.92	318038.4

[1] Sugar Statistics, February 98:vol.29, No.6

Sugar

India is one of the major plantation white sugar manufacturers in the world with an output of over 200 lakh tonnes in the 1995–96 season. Most of the sugar mills are situated in the cane growing areas in the countryside and operate for anywhere from 5–10 months of the year. There are about 393 large and medium scale sugar mills in India. Of these, about 26% of the units are yet to attain satisfactory performance level with regard to installation and operation of effluent treatment plants (CPCB 1997). The sugar manufacturing process consists of the following steps : a) extraction of sugarcane b)clarification of the juice by the addition of lime and sulphur dioxide to heated juice at 70°C c) concentration of the clear juice after clarification to 60% solids d) syrup sulphitation and crystallization e) centrifugation, drying and bagging the sugar crystals. The manufacturing process produces wastes such as baggase and press mud. The former is normally used as fuel in boilers while the latter is employed either for soil enrichment or for biomethanation. In addition, the process generates wastewater, with the following typical characteristics:

Wastewater generation	0.2 to 1.8 m^3/tonne of sugar manufacture
pH	4–7
COD	1800–3200 mg/litre
BOD	720–1500 mg/litre
Total suspended solids	670 mg/litre
Total dissolved solids	2800 mg/litre
Sulphates	300 mg/litre

Apart from the effluent, the sugar cane press mud is also treated by anaerobic digestion. According to a respondent, the organic content of this waste is 1,10,000 mg/litre of COD and 80,000 mg/litre of BOD. About 4 tonnes of press mud becomes available for every 100 tonnes of sugar cane crushed. At one of the sugar factories in Karnataka state, four KVIC (khadi and village industries commission) floating type biogas plants, each having a capacity of 85 m^3, have been installed. The influent slurry has a total solids content of 5% and the HRT is 18 days. The plant is able to produce about 100 litre of biogas per kg of press mud with a methane content of 55%. The COD removal efficiency works out to 75%.

Sugarmill wastewater is acidic in nature and thus requires pH correction prior to anaerobic treatment. Since sugar manufacturing is a seasonal activity, the process needs to be restarted at the beginning of every season. All the respondents of our questionnaire have installed a two stage process (anaerobic followed by aerobic) for wastewater treatment with a reported COD reduction of 70–75% in the anaerobic process. However, no design details are available.

Radwan and Ramanujam (1995) have attempted the use of rotating biological contactor (RBC) for the treatment of synthetic sugar effluent. COD reduction was reported in the range of 90–97 %. A pilot scale study on a 2.83m^3 capacity UASB reactor at a sugar mill at Satha, Aligarh in northern India demonstrated a COD reduction of up to 80% (Khursheed, Farooqi and Siddiqui 1997). The unit was operated at 34°C and 730 mm Hg pressure with a HRT of 5.5 h and an average COD loading rate of 13 kg /m^3 d. The average methane gas recovery was 0.22 m^3 CH_4/kg COD removed. The methanogenic activity of the sludge, sludge yield coefficient and the SRT was 0.56 kg COD-CH_4/kgVSS d, 0.34 kg VSS/kg COD and 34 days respectively.

A tonne of sugar produced has the ability to generate energy equivalent to 0.19 kg LPG from wastewater and 16.6 kg LPG from pressmud if treated anaerobically. The potential of energy generation from sugar industry waste is given in Table 26. It is possible to produce energy equivalent to 0.2 million tonne LPG per year from sugar industry waste alone.

Table 26 Energy generation potential of sugar industry waste (production figures for the year 1994-95)

aStates	*Installed capacity*[1] (Lakhs tonnes)	*Energy potentional* (tonne LPG)
AP	6.35	10661.65
Bihar	4.12	6917.48
Gujarat	8.11	13616.69
Karnataka	8.37	14053.23
Maharashtra	38.34	64372.86
Madhya Padesh	0.99	1662.21
Punjab	6.25	10493.75
Rajasthan	0.23	386.17
Tamil Nadu	11.84	19879.36
Uttar Pradesh	32.06	53828.74
India	122.2	205173.8

[1] Cier's industrial databook 1998.

Tannery

There are about 2000 tanneries in India of which 90 % are in the small scale sector and located primarily in the states of Tamil Nadu, Uttar Pradesh, West Bengal and Punjab. The country has about 85 large and medium scale tanneries, of which about 40% of the units are yet to attain satisfactory performance level with regard to installation and operation of effluent treatment plants (CPCB 1997). Large quantities of wastewater characterised by strong colour, high BOD, high pH and high dissolved solids is discharged in the tanning process. Depending upon the type of the tanning process, about 30 to 40 litre of effluent is generated per kg of hide treated (NIPFP 1989). The tanning process basically has three stages : a) preparation of hides which consists of operations such as liming and pickling b) tanning proper which is carried out either by using vegetable tannins or inorganic chromium salts and c) finishing. Typical characteristics of the composite wastewater of an Indian tannery are (Kaul, Nandy and Trivedy 1997):

Wastewater flow	30 to 40 litre per kg of hide processed
pH	7.5 to 12.5
Suspended solids	2800–3300 mg/litre
BOD	720–840 mg/litre
COD	3400 – 5100 mg/litre
Total phosphorus as P	1.2–5.0 mg/litre
Total nitrogen as N	120–140 mg/litre
Chlorides	1340–4200 mg/litre

Prior to anaerobic treatment of the wastewater, it is necessary to adjust the pH and to effect the removal any chromium, if present. For the latter, various physico-chemical treatment technologies are well established and practiced in India. Rajamani and coworkers (1995) studied the performance of a 10,000 litre capacity UASB reactor installed at Pioneer tannery in Kanpur, Uttar Pradesh . The plant was designed to treat 20–40 m^3/d of combined tannery (excluding pickle and chrome liquor) effluent. It is possible to reduce suspended solids, BOD and COD content by 70%, 60% and 70% respectively at 12–16 hours HRT. The SRT was about 20 days. The biogas yield was 0.15–0.25 m^3/kg of COD removed with a methane content of 80%. The reasons for low yield of biogas were attributed to sulphate reduction and some escape of gas along with the effluent. To meet the discharge standards, the effluent from the UASB process was subjected to aerobic post treatment. The treatment of tannery effluent in a fixed film reactor has also been attempted (Kaul, Daryapurkar and Szpyrkowicz 1997).They observed the COD removal efficiency to be 66% with a methane yield of 0.3 m^3/kg COD removed.

Based on actual operating plant data, it is estimated that by the anaerobic digestion of wastewater, tanneries have the potential to generate 0.004 kg LPG equivalent energy per kg of hide processed.

Dairy

There has been a remarkable growth in milk production and milk processing centers (dairies) in India. The dairies collect the milk from the producers and then either simply bottle it for marketing or produce different milk food. There are 127 large and medium scale integrated dairy plants in India. Of these, about 50% of the units are yet to attain satisfactory performance level with regard to installation and operation of effluent treatment plants (CPCB 1997). The liquid waste from a dairy originates from several sources such as the receiving station, bottling plant, cheese plant, butter plant, condensed milk plant, dried milk plant and icecream plant. The characteristics of the composite wastewater of an integrated dairy are CPCB (1993):

Wastewater generation	2 litre per litre of milk processed in case of chilling plant and 4.5 litre per litre of milk processed in an integrated plant
pH	5.6–8
Oil and grease	68–240 mg/litre
Suspended solids	28–1900 mg/litre
COD	1120–3360
BOD	320–1750

Pilot scale experiments have been conducted on a 20m^3/d fixed film reactor for biomethanation of dairy wastewater (Roy and Chaudhuri 1996). The reactor was packed with plastic media up to a height of 2.23 m leaving a gap of 0.4 m at the bottom. COD feeding into the digester was 40 kg/day and the designed mean cell residence time was 25 days. About 77 % COD reduction was achieved and the methane gas production at STP was 0.33 m^3/m^3 of wastewater.

Feasibility studies on the treatment of simulated dairy wastewater has also been attempted in a 2.8L capacity upflow anaerobic expanded sludge bed reactor (Mehrotra and Jain 1997). The reactor was found to remove COD litre 90% at a loading rate of 8 kg COD/m^3 d and optimum HRT of 8–10 h. Specific gas yield was observed to be 0.41m^3 CH_4/kg COD with a sludge loading rate of 0.6 g COD /g VSS d.

The potential of energy generation from dairy industry effluent (assuming 3L wastewater produced per liter of milk processed) is 0.84 kg LPG equivalent per m^3 of milk processed. The effluent needs simple post-treatment to meet the discharge standards. The statewise energy generation potential from dairy industry wastewater is shown in Table 27. From these figures, it is estimated that 0.05 million tonne LPG equivalent energy can be generated on a country wide basis by the anaerobic digestion of dairy industry wastewater.

Table 27 Energy generation potential from dairy industry wastewater(all figures are for the year 1994-95)

States	*Milk production*[1] ('000 tonnes)	*Energy potential* (tonne LPG)
Andhra Pradesh	3223	2707.3
Assam	713	598.9
Bihar	3582	3008.9
Gujarat	3995	3355.8
Haryana	4140	3477.6
Himachal Pradesh	707	593.9
Jammu and Kashmir	701	588.8
Karnataka	2938	2467.9
Kerala	2301	1932.8
Madhya Pradesh	5662	4756
Maharashtra	4810	4040.4
Manipur	91	76.44
Meghalaya	51.5	43.26
Nagaland	67	56.28
Orissa	591	496.4
Punjab	6249	5249.1
Rajasthan	4951	4158.8
Tamil Nadu	4184	3514.6
Tripura	38	31.9
Uttar Pradesh	11288	9481.9
Sikkim	34	28.6
West Bengal	3733	3135.7
Total	64049.5	53801.6

[1] Cier's industrial databook 1998.

Pulp and paper

Indian paper mills can be broadly classified into large mills (with a production capacity of more than 10,000 tonnes per annum), small mills (producing less than 10,000 tonnes per annum) and small waste paper based mills. The pulp used by the mills is produced utilizing different cellulosic materials such as bamboo, bagasse, rice or wheat straw and waste paper. Most of the large paper mills in India are integrated pulp and paper mills, while a few produce pulp only and some purchase pulp to produce paper only. Of the 279 large pulp and paper mills, 68% do not have adequate wastewater treatment facilities (CPCB 1997). Pulp is conventionally manufactured either by the Kraft process, sulphite process or by mechanical pulping though majority of the Indian mills use the Kraft process. This involves digestion of chipped cellulosic raw material with chemicals like sodium sulphate, sodium hydroxide and sodium sulphide at high temperature and pressure. After digestion, the pulp is washed and bleached and sent to the paper mill. The volume and characteristics of the wastewater generated varies widely and depends upon the size of operation, manufacturing process, raw material used and conservation measures adopted. Based on the responses of our questionnaire survey, the wastewater characteristics of the pulp and paper mills are as follows:

Wastewater generated	230 m^3/tonne of paper produced
Temperature	36–38°C
pH	6.5–8.5
Suspended solids	300–700 mg/litre
BOD	50–150 mg/litre
COD	250–500 mg/litre
Colour	Dark brown

In addition, pulp and paper mill effluents contain variable amounts of materials that are toxic or inhibitory to biological process. The effects of these can be partially mitigated by equalisation of the wastewater, pH correction, nutrient addition and by incorporation of recycle and bypass facilities.

All the respondents to the questionnaire employ activated sludge process for wastewater treatment. A plant visited by the team at Pudumjee Pulp and Paper Mills, Pune, had the CSTR type anaerobic treatment plant of 13000 m^3 volume (fig. 7). BOD and COD removal efficiency was reported to be 85–90% and 65–70% respectively.

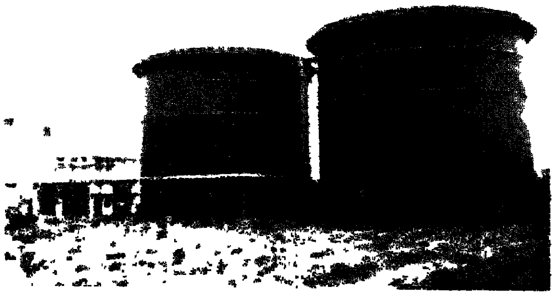


Figure7 Anaerobic treatment plant, Pudumjee Pulp and Paper Mills, Pune

An UASB based pilot plant has recently been commissioned at Satia paper mills. Punjab (Bioenergy News 1997). The plant has a capacity of 3.81 m^3 and was operated at a COD loading rate of 10 kg COD/ m^3 d. BOD and COD reduction was quoted as 80% and 52% respectively with a biogas yield of 0.4 m^3/kg of COD reduced with 72% methane content. Based on this experience, paper mills could generate about 9 kg LPG equivalent energy from their wastewater per tonne of paper produced. During the year 1996–97 the total production of paper in India was 3941 thousand tonnes (Cier's data book 1998) which means that about 0.035 million tonne LPG equivalent energy could have been generated if the wastewater was treated by the anaerobic process.

lible oil

The recovery of oil from oil bearing material is typically carried out by solvent extraction and consists of the following steps:

1. Preparation: The oil seeds are cleaned and then cooked with steam to loosen the oil bearing cells before crushing them into thin flakes. These flakes are then passed through an expander to convert them into 'collects'.
2. Extraction: The collects are treated with food grade hexane to extract the oil. The solvent is thereafter recovered and reused. The oil meal also contains about 30% solvent and is sent for drying and toasting before being bagged in gunny bags
3. Refining: The crude oil contains impurities such as phosphatides, free fatty acids, colour and odour and is refined as follows:

   Degumming. This is carried out by by treating the crude oil with phosphoric acid and water at 60°C and centrifuging the precipitated gummy matter.

   Neutralization. The degummed oil is treated with caustic soda lye at 80°C The free fatty acid is converted to soap of higher molecular weight which can be further treated with sulphuric acid to convert soap to acid oil.

   Bleaching. The degummed and neutralized oil is treated with bleaching earth and activated carbon.

Deodourisation. Since the bleached oil has an unpleasant odour, the odoriferous substances are removed by steam distillation at elevated temperature and pressure. After cooling and filtration, the refined oil is ready for packing.

The entire extraction and refining process generates effluents with the following typical characteristics:

Wastewater generation	57 litre/tonne of refined oil production
pH	5.0–10
Oil and grease (O&G)	400
COD	3200–6000 mg/litre
BOD	2100

The break down for the various processing steps is as follows:

	pH	*Protein* (mg/litre)	*COD* (mg/litre)	*O&G* (mg/litre)	*TDS* (mg/litre)
Solvent extraction plant	7.5-8.0	100	1000	-	-
Refinery plant	3.0-4.0	-	12000	400	-
Boiler house	12.0	-	-	-	3000

Information pertaining to the anaerobic treatment of edible oil wastewater could not be collected during the survey. However, looking at the effluent characteristics, it appears that anaerobic treatment would be feasible and therefore needs to be further investigated. Assuming that a suitable reactor could be developed for 70% reduction in COD with a methane yield of 0.2 m^3 kg of COD destroyed, the energy generation potential from wastewater of an edible oil manufacturing plant would be about 0.34 kg LPG equivalent per tonne of oil produced (Table 28). Production of edible oil during the year 1994–95 touched 7 million tonnes. From this, the potential of energy generation from edible oil manufacturing industries would be 0.0024 million tonnes of LPG equivalent.

Table 28 Production of edible oil in India

Oil source	Production ('000 tonne)
Groundnut	1936
Mustard & Rapeseed	1835
Sesame	228
Safflower	80
Niger	76
Soyabean	574
Sunflower	483
Cottonseed	400
Coconut	350
Vanaspati	945

Source Cier's data book 1998

Textile

The textile industry is broadly classified on the basis of the fibers used viz. cotton, woollen or synthetics. The process involves production of fibre/yarn and preparation of cloth and an integrated plant carries out both these steps. A large number of textile mills in India are categorized under the small scale sector involving activities like designing, bleaching, mercerizing, dyeing, printing etc. These processes are either carried alone or in combination and are responsible for generating bulk of the liquid waste. Of the total 559 large and medium size textile industries in India, 66% are yet to install adequate wastewater treatment facilities (CPCB 1997). Based on the responses of the questionnaire survey, the following are the characteristics of the wastewater from textile industries.

Parameter	*Cotton*	*Rayon Yarn*	*Nylon*	*Polyester Yarn*	*Jute*
Wastewater generated (m^3/tonne of production)	6 m^3/m	775	18	4	3.5
Temperature	NA	32	30	Ambient	NA
pH	8.5-9.8	6.0	7.8	7.0-7.5	7.5-8.5
Suspended solids (mg/litre)	330-360	123	NA	250-300	40
BOD (mg/litre)	175-240	33	3000	300-350	20
COD (mg/litre)	350-450	115	4000	800-1000	85
Oil and grease (mg/litre)	25-80	NA	NA	NA	NA

NA - not available

Since the sample size of the responses received was small, the above characteristics were ratified with literature data. An audit done by National Environmental Engineering Research Institute (NEERI) at one of the integrated cotton textile mills in India quoted the COD value as 500–680 mg/litre, BOD as

150–230 mg/litre, suspended solids as 180–300 mg/litre, pH as 8.8–9.0 and oil and grease as 20–25 mg/litre (NEERI 1993). These values are in fair agreement with the ones obtained by us. The characteristics of the composite waste from a viscose rayon plant specifies 35–210 mg/litre COD and 190–200 mg/litre suspended solids (Rao and Dutta 1979) which is again close to the values quoted by the respondent. Textile wastewater is also characterized by the presence of high colour, dissolved solids, dyes and zinc (especially in synthetic textiles).

All the respondents to our questionnaire have adopted a combination of physico-chemical treatment and activated sludge process for the wastewater treatment. Few studies have been performed to assess the applicability of anaerobic treatment. Ilangovan and Briones (1997) studied the EGSB (expanded granular sludge blanket) reactor for treatment of textile effluent. Significant decolorization (76–80%), and COD removal (54–60%) were obtained at high upflow velocity (0.9 m/hr) and low COD/SO_4 (5–6 mg/litre) levels.

NEERI has conducted a treatability study on anaerobic fixed film fixed bed reactor for the treatment of composite wastewater from a textile industry cluster. The wastewater had a BOD of 280 mg/litre and COD of 1160 mg/litre (NEERI 1993). The reactor was filled with 25 mm pieces of refractory bricks which provided the medium for bacterial attachment. The system was operated at different HRTs and organic loading rates. About 67% BOD removal was achieved at 1.0 day HRT and an organic loading rate of 0.25 kg BOD/m^3 d. The biogas yield was 0.17 m^3/kg COD removed and was composed of 62% methane. However, further pilot scale studies are still needed to evaluate the applicability of anaerobic processes for treatment of textile industry wastewater. The problem of effluent pretreatment and post treatment for the removal of dyes/colour should also be simultaneously tackled along with the anaerobic digestion aspect.

Slaughter house

The wastewater characteristics and volume depends on the extent of further processing of the slaughtered animals as well as on the primary treatment options adopted by the slaughter house to separate the liquid from the solid residues. Slaughter house wastewater is distinguished by a high level of suspended solids and the digestion process is prone to scum formation. One of the modern slaughter houses at Hyderabad having a capacity for processing 500 buffaloes and 1500 sheep generates the following wastewater (personal communication):

Quantity	2000 m^3/day
pH	6–7
Total Solids	6000–8000 mg/litre
BOD	3500–4000 mg/litre
COD	6000–8000 mg/litre

The same unit has installed an UASB system for the treatment of wastewater. Prior to anaerobic treatment, the wastewater is subjected to equalisation followed by primary digestion. The UASB effluent is treated in an aeration tank to meet the discharge standard. The anaerobic stage is able to reduce the COD and BOD by up to 80% and 90% respectively. The total biogas production is 3500–4500 m^3/d with a methane content of 65%.

Studies by Song, Kwon and Park (1997) also confirm the viability of the UASB process for slaughterhouse effluent treatment. They observed a COD removal of over 80% when operating at a HRT of 12–19 hours with a loading rate of 1.0 kg-COD/m^3 d.

Kang and Tritt (1997) investigated a 2.8 m^3 pilot scale fixed film reactor for the treatment of slaughter house wastewater. Bamboo rings were choosen as support media. The reactor performance displayed a maximum of 95% COD removal efficiency at an organic loading rate of 1 kg COD/m^3 d at a HRT of 7.5 days. At a higher OLR (organic loading rate) of 4 kg COD/m^3 d, the COD removal efficiency was 75% at a HRT of 2 days. The COD removal efficiency remained constant irrespective of whether the reactor was operated in the upflow or the downflow mode.

Coffee

Coffee processing is a seasonal industry which normally operates from November to February. The process includes pulping of fruit to remove outer skin and mucilage and cleaning of seeds. The process is quite water intensive and generates about 5 m^3 wastewater per tonne of fresh coffee fruit processed. Typical pulping wastewater characteristics are as follows (Bioenergy News 1997):

pH	5–5.5
Suspended solids	311 mg/litre
Volatile suspended solids	82 mg/litre
BOD	1510 mg/litre
COD	2800 mg/litre

The effluent composition indicates that it has a good potential for biomethanation. However, no practical case study is available in India. Fernandez and Chacin (1997) studied the treatment of simulated wastewater from coffee under thermophilic and mesophilic conditions and concluded that mesophilic anaerobic digestion can be used successfully to treat synthetic, ground coffee waste and that a better performance could be achieved by avoiding the potassium inhibitory effect by the use of calcium in the reactor feed. However, no data on the gas yield was reported. If we assume a 70% COD reduction by anaerobic digestion along with a gas yield of 0.3 Nm^3/kg COD removed and a methane content of 65%, then coffee effluent has the potential to generate 1.45 kg LPG equivalent energy per tonne of coffee produced. In the year

1994–95 India manufactured about 43 thousand tonnes coffee (Ceir's industrial survey 1998) which works out to 62 thousand tonnes of LPG per annum from the corresponding effluents.

5 Conclusions & recommendations

This work investigates the potential of bioenergy generation from the anaerobic digestion of industrial wastewater in India. Apart from estimating the biogas production from various agrobased effluents, the current technology status as well as the Indian government regulations with respect to pollution prevention are also discussed. The following points emerge from this study:

1. Though anaerobic digestion systems have been operational in certain industries like distilleries for some time, there is still some apprehension regarding adopting this technology in other sectors. This stems from various factors like limited availability of experienced consultants to implement the technology, little full scale experience, lack of operator training within the industries for process maintenance and restricted interaction between research organizations and commercial developers/vendors.
2. Based on organic loading rate, cost and energy considerations, UASB (upflow anaerobic sludge blanket) reactor appears to be the most viable option. However, it requires relatively specialized operating skills since it is incapable of handling shock loads. It has also been noticed that most of the UASB installations in India lack granular sludge formation and thus they do not fully exploit the benefits of this configuration.
3. The total energy generation potential from the anaerobic digestion of agrobased industrial wastewater is estimated to be 0.67 million tonne LPG equivalent per annum. If the biogas is further used for power generation in gas turbines, the total electricity production (assuming 38% efficiency) works out to 365 MW.
4. The maximum bioenergy generation potential exists in distilleries and sugar mills, which together can generate 0.52 million tonne LPG equivalent per annum. However, the technology for using press mud for biomethanation in the sugar industry requires further investigation.
5. Anaerobic digestion systems are yet to be fully established in tanneries and pulp and paper mills. A majority of the industries in these two sectors are in the medium and small scale with poor waste management and resource recovery practices. An additional challenge lies in segregation or pretreatment of the effluent stream to remove toxic substances (like chromium in tannery wastewater) prior to anaerobic treatment.
6. Effluents from edible oil manufacture and coffee pulping units can be treated anaerobically. However, little work has been done in this area and therefore pilot scale testing is required.

7. Since a large number of Indian industries are yet to establish adequate wastewater treatment facilities, the Government of India is actively promoting anaerobic digestion technology. Apart from funding pilot studies, financial and fiscal incentives are also provided for establishing full scale plants. Also, under the UNDP/GEF assistance programme, MNES is encouraging both national and international entrepreneurs to demonstrate proven anaerobic technologies in various industrial and domestic sectors.

This survey provides only a preliminary indication of the biogas generation potential in India from various industrial effluents. Though over 300 questionnaires were sent out, only around 10% of the subjects responded, indicating a general apathy and disinterest among the industries. Thus, the survey does not provide a complete picture of the current status of the technology in the country. A more detailed study comprising several field trips is essential to gather and collate further information regarding the implementation status, actual system performance, operational / maintenance problems as well as possible technical innovations required for wider acceptance of the technology. In addition, there is an urgent need for more intensive interaction between research organizations and suppliers of anaerobic systems. This is supported by the fact that over the last 15 years, even though MNES has sponsored more than 90 research oriented projects on biogas production, there is still lack of sufficient design information. Out of the nearly 60 demonstration projects, only one has been scaled up for commercial operation. This indicates a wide gap between R&D efforts and technology implementation and thus, more work is essential on the following aspects :

- Determination of kinetic constants for various combinations of wastewater and reactor types
- Scale up formulations for different reactor systems
- Biochemical pathways of various organic compounds and determination of the rate limiting step(s)
- Mathematical modeling for optimization of the process conditions, reactor size and overall system cost.

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Annexure I

Wastewater discharge standards (CPCB 1995)

Dye & dye intermediate industry

Parameters	*Concentration not to exceed, mg/litre (except pH, colour and bio-assay test)*
pH	6.0-8.5
Colour, Hazen unit	400
Suspended Solids	100
BOD (5 days at 20°C)	100
Oil & Grease	10
Phenolics as C_6H_5OH	1
Cadmium as Cd	2.0
Copper as Cu	3.0
Manganese as Mn	2
Lead as Pb	0.1
Mercury as Hg	0.01
Nickel as Ni	3
Zinc as Zn	5
Chromium as Cr	2.0
Hexavalent	0.1
Total	2
Bio-assay test	90 per cent survival in 96 hours

Fermentation industry (distilleries, maltries & breweries)

Parameters	*Concentration in the effluent not to exceed, (except for pH, colour and odour)*
pH	5.5 to 9.0
Colour & Odour	Absent
Suspended Solids	100
BOD (5 days at 20°C)	
- disposal into inland surface waters	30
- disposal on land	100*

*500 - The Gazette of India Extraordinary, Part II-Section 3
- Sub-section (ii) S.O., 12 (E), January 8, 1990, New Delhi

Food & fruit processing industry

	Concentration not to exceed				*Quantum*
Category	pH	*Suspended solids,* mg/litre	*Oil & grease* mg/litre	*BOD$_5$ at 20°C* mg/litre	grams/tonne of product
A. Soft drinks					
a) Fruit based/synthetic (more than 0.4 MT/day) Bottles and tetrapack	6.5-8.5	100	10	30	
b) Synthetic (<0.4 MT/day)	Disposal via septic tank				
B. Fruits & Vegetables					
a) Above 0.4 MT/day	6.5-8.5	50	10	30	-
b) 0.1 - 0.4 MT/day	6.5-8.5	-	-	300*	-
C. Bakery					
a) Bread and Biscuit					
1. Continuous process (more than 20T/day)	6.5-8.5	-	-	200*	25
2. Noncontinuous Process (less than 20T/Day)	Disposal via septic tank				
b) Biscuit production					
1. 10T/Day & above	6.5-8.5	-	-	300*	35
2. Below 10 T/Day	Disposal via septic tank				
D. Confectionaries					
a) 4 T/Day & above	6.5-8.5	50	10	30	-
b) Below 4 T/Day	Disposal via septic tank				

Note: To ascertain the category under which the unit falls, the average of daily production and wastewater discharge for the preceding 30 operating days from the date of sampling shall be considered

* The standard shall be reviewed by 1992 and stringent standards shall be prescribed with respect to BOD

** The emission from boiler house shall conform to the standards already prescribed under EPA 1986 vide Notification No. GSR 742 (E), 30.8.90

Cotton textiles industry (composite & processing)

Parameters	Concentration not to exceed (except for pH & Bio-assay)
Common	
pH	5.5 to 9.0
Suspended Solids	100
BOD (5 day at 20°C)	150
Oil & grease	10
Bio-assay test	90% survival of fish after 96 hrs.
Special	
Total chromium (as Cr)	2
Sulphide (as S)	2
Phenolic compounds as (C_6H_5OH)	5

Large pulp & paper/news print/rayon grade pulp plants of capacity above 24000 MT/annum

Parameters flow	Standards
(1) (Large pulp & paper)	Flow 200 m^3/tonne of paper
(2) (large rayon grade/news print)	150 m^3/tonne of paper
pH	7.0-8.5
Suspended solids, mg/litre	100
BOD (5 days at 20°C), mg/litre	30
COD, mg/litre	350
TOCL*	2.0 kg/tonne of paper produced

*Total organic chlorides

Leather industry

Concentration in the effluents not to exceed, mg/litre (except for pH and per cent sodium)

	Mode of disposal			
Parameters	*Inland surface water*	*Public sewer*	*Land for irrigation*	*Marine coastal areas*
Suspended solids	100	600	200	100
BOD (5 days at 20°C)	30	350	100	100
pH	6.0 to 9.0	6.0 to 9.0	6.0 to 9.0	6.0 to 9.0
Chlorides as (Cl)	1000	1000	200	–
Chromium				
Hexavalent	0.1	0.2	0.1	1.0
Total	2.0	2.0	2.0	2.0
Sulphides (as S)	2.0	5.0	–	5.0
Sodium per cent	–	60	60	–
Boron (as B)	2.0	2.0	2.0	–
Oil & grease	10	20	10	20

Pharmaceutical industry

Parameter	Limits in mg/litre (except pH)
Compulsory parameters	
pH	5.5-9.0
Oil & grease	10
BOD_5 at 20°C[1]	100
Total suspended solids	100
Bioassay test[2]	90% survival after 96 hours in 100% effluent
Additional parameters[3]	
Mercury	0.01
Arsenic	0.2
Chromium (Hexavalent)	0.1
Lead	0.1
Cyanide	0.1
Phenolics (C_6H_5OH)	1.0
Sulfides (as S)	2.0
Phosphate (as P)	5.0

Note

[1] The limit of BOD_5 at 20°C will be 30 mg/litre if effluent is discharged directly to fresh water body.

[2] Test should be carried out as per IS. 6582-1971

[3] The additional parameters are applicable to bulk drug manufacturing units depending upon the process and product

[4] No limit for COD is prescribed, but it should be monitored. If the COD of the treated effluent is greater than 250 mg/litre such industrial units are required to identify chemicals causing the same. In case these are found to be toxic, as define in Hazardous Chemical Rules, 1989 (Schedule I), the State Boards in such cases shall direct the industries to install tertiary treatment system within the stipulated time limit. Otherwise COD may not be stipulated. This may be done on a case-to-case basis.

Slaughterhouse, meat & sea food industry

Category	Concentration not to exceed, limit in mg/litre		
	BOD	*TSS*	*Oil & grease*
A. Slaughterhouse			
a) Above 70 TLWK[*]	100[**]	100	10
b) 70 TLWK & below	500	–	–
B. Meat Processing			
a) Frozen meat	30	50	10
b) Raw meat from own slaughter house	30	50	10
c) Raw meat from other sources	Disposal via Screen and Septic tank		
C. Sea Food Industry	30	50	10

[*] TLWK - Total Live Weight Killed

*** Standar shall be reviwed by 1992 and stringent standards shall be prescribed with respect to BOD

Small pulp & paper industry

Mode of disposal	*Parameters*	*Concentration not to exceed, mg/litre (except for pH and sodium absorption ratio)*
Inland surface water	pH	5.5- 9.0
	Suspended solids	100
	BOD (5 days at 20°C)	30
On land	pH	5.5-9.0
	Suspended solids	100
	BOD, 5 day at 20°C	100
	Sodium absorption ratio	26

Small scale industry

Sl No	*Parameters*	*Concentration not to exceed, limits in mg/litre (except pH, temperature and bioassay test*
1	Mercury (Hg)	0.01
2	pH	5.5 to 9.0
3	Suspended solids	250
4	Biochemical oxygen demand (5days at 20°C)	150
5.	Temperature	Shall not exceed 5°C above the ambient temperature of the receiving bo
6.	Free available chlorine	0.5
7.	Oil & grease	10
8.	Cu (Total)	3.0
9.	Iron (Total)	3.0
10.	Zinc	5.0
11.	Cr (Total)	3.0
12	Phosphate (as P)	5.0
13.	Bioassay test	90% of test animals survival after 96 h with 1:8 dilution
14	Sulphide (as S)	2
15	Phenolic compounds (as C_6H5_5OH)	5
16	Hexavalent chromium (as Cr)	0.1
17	Nickel (as Ni)	3.0
18	Cadmium (Cd)	2.0
19	Chloride (as Cl)	1000
20	Sulphide (as SO_4)	1000
21	Cyanides (as CN)	0.2
22	Ammoniacal Nitrogen (as N)	50
23	Lead (as Pb)	0.1
24	Total metal	10.0

Note The standards may be relaxed in cases where the wastewater from small scale industrial units are collected and treated in a Terminal Treatment Plant. These standards are laid down without prejudice to the Board varying or modifying them while issuing contents pursuent to Section 25 and 26 of the Water (Prevention and Control of Pollution) Act, 1974.

Sugar industry

Parameters	*Concentration not to exceed, mg/litre*
BOD (5 days at 20°C)	100 for disposal on land
Suspended solids	30 for disposal in surface waters
	100 for disposal on land
	30 for disposal in surface waters

Tannery effluents disposal standards (after primary treatment): channel/conduit carrying wastewater to secondary treatment plant

Type of tanneries	*Parameters*	*Concentration limit not exceed, mg/litre (except pH)*
Chrome tannenes/combined chrome & vegetable tannenes		
	pH	6.5-9.0
	Suspended solids	Not to exceed 600
	Chromium concentration after treatment in the chrome waste water stream	45
Vegetable tannenes		
	pH	6.5-9.0
	Suspended solids	Not to exceed 600

Tanneries

Parameter	*Concentration in mg/litre except pH*	*Quantum per raw hide processed*
pH	6.5-9.0	–
*BOD (5 days at 20°C)	100	–
Suspended solids	100	–
Sulphides (as S)	1	–
Total Chromium (as Cr)	2	–
Oil and grease	10	–
Waste water generation	–	28 m^3

* For effluent discharge into inland surface waters BOD limit shall be made stricter to 30 mg/litre by the concerned State Pollution Control Boards

Dairy industry: effluent standards

Parameter	*Concentration in mg/litre, except pH*	*Quantum per product processed*
pH	6.5-8.5	–
*BOD (5 days at 20°C)	100	-
**Suspended solids	150	–
Oil and grease	10	–
Waste water generation	–	3 m^3/kilo litre of milk

Schedule VI of Environment (Protection) Third Amendment rules, 1993

General Standards* for discharge of environment pollutants

Part- A : Effluents

Sl. No.	*Parameters*	*Standards*			
		Inland water	*Public sewers*	*Land for irrigation*	*Marine coastal area*
		(a)	(b)	(c)	(d)
1.	Colour and odour	See Note 1	–	See Note 1	See Note 1
2.	Suspended solids, mg/litre, Maximum	100	600	200	a. For process waste water For cooling water effluent- cent above total suspende matter of influent cooling
3.	Particle size of suspended solids	shall pass 850 micron IS Sieve			b. Floatable solids, Maxim mm Settleable solids Maximu microns.
4.	Dissolved solids (inorganic), mg/litre maximum	2100	2100	2100	–
5.	pH value	5.5-9.0	5.5-9.0	5.5-9.0	5.5- 9.0
6.	Temperature °C, Maximum	Shall not exceed 40 in any section of the stream within 15 meters down stream from the effluent outlet	45 at the point of discharge	–	45 at the point of discharg
7.	Oil and grease, mg/litre, maximum	10	20	10	20
8.	Total residual chlorine, mg/litre, Maximum	1.0	–	–	1.0
9.	Ammonical nitrogen (as N), mg/litre, Maximum	50	50	–	50
10.	Total Kjeldahl nitrogen (as N), mg/litre, Maximum	100	–	–	100
11.	Free Ammonia (as NH_3), mg/litre, Maximum	5.0	–	–	5.0

Sl. No.	Parameters	Standards			
		Inland water	*Public sewers*	*Land for irrigation*	*Marine coastal areas*
		(a)	(b)	(c)	(d)
12	Biochemical oxygen demand (5 days at 20°C) Maximum	30	350	100	100
13	Chemical Oxygen demand, mg/litre, Maximum	250	–	–	250
14	Arsenic (as As), mg/litre, Maximum	0.2	0.2	0.2	0.2
15	Mercury (As Hg), mg/litre, Maximum	0.01	0.01	–	0.01
16	Lead (as Pb), mg/litre, Maximum	0.1	1.0	–	1.0
17	Cadmium (as Cd), mg/litre, Maximum	2.0	1.0	–	2.0
18	Hexavalent chromium (as Cr^{+6}) mg/litre, Maximum	0.1	2.0	–	1.0
19	Total chromium (as Cr), mg/litre, Maximum	2.0	2.0	–	2.0
20	Copper (as Cu), mg/litre, Maximum	3.0	3.0	–	3.0
21	Zinc (as Zn), mg/litre, Maximum	5.0	15	–	15
22	Selenium (as Se), mg/litre, Maximum	0.05	0.05	–	0.05
23	Nickel (as Ni), mg/litre, Maximum	3.0	3.0	–	5.0
24	Boron (as B), mg/litre, Maximum	2.0	2.0	2.0	–
25	Percent sodium, Maximum	–	60	60	–
26	Residual sodium carbonate, mg/litre, Maximum	–	–	5.0	–

Sl. No.	Parameters	Standards			
		Inland water	*Public sewers*	*Land for irrigation*	*Marine coastal areas*
		(a)	(b)	(c)	(d)
27	Cynide (as CN), mg/litre, Maximum	0.2	2.0	0.2	0.2
28	Chloride (as Cl), mg/litre, Maximum	1000	1000	600	–
29	Fluoride (as F), mg/litre, Maximum	2.0	15	–	15
30	Dissolved phosphates (as P), mg/litre, Maximum	5.0	–	–	–
31	Sulphate (as SO_4), mg/litre, Maximum	1000	1000	1000	–
32	Sulphide (as S), mg/litre, Maximum	2.0	–	–	5.0
33	Pesticides	Absent	Absent	Absent	Absent
34	Phenolic compounds (as C_6H_5OH) mg/litre, Maximum	1.0	5.0	–	5.0
35	Radioactive materials: (a) Alpha emitters MC/ml., Maximum (b) Beta emitters μc/ml. Maximum	10^{-7} 10^{-6}	10^{-7} 10^{-6}	10^{-8} 10^{-7}	10^{-7} 10^{-6}

Note

1. All efforts should be made to remove colour and unpleasant odour as far as practicable.
2. The standards mentioned in this notification shall apply to all the effluents discharged, such as industrial mining and mineral processing activities, municipal sewage., etc.

* There standares shall be applicable for industries, operations or processes other than those industreis, operations or process for which standars hav e seen specificied in Schedule I.

Part-B: Wastewater generation standards

S.No.	Industry	Quantum
1.	Integrated iron & steel	16 m^3/tonne of finished steel
2.	Sugar	0.4 m^3/tonne of cane crushed
3.	Pulp & paper	
	(a) Large pulp & paper	
	(i) Pulp & paper	175 m3/tonne of paper produced
	(ii) Rayon grade pulp	150 m3/tonne of paper
	(b) Small pulp & paper:	
	(i) Agroresidue based	150 m3/tonne of paper produced
	(ii) Waste paper based	50 m3/tonne of paper produced.
4.	Fermentation Industries	
	(A) Maltry	3.5 m3/tonne of grain consumed
	(b) Brewery	0.25 m3/kilo litre of beer produced
	(c) Distillery	12 m3/KL of alcohol proudced
5.	Caustic soda	
	(a) Membrane cell process	1 m3/tonne of caustic soda produced excluding cooling tower blowdown
	(b) Mercury cell process	4 m3/tonne of caustic soda produced (mercury bearing). 10% blow down permitted for cooling tower.
6.	Textile Industries:	
	Man-made fibre	
	(i) Nylon & Polyester	120 m3/tonne of fibre produced
	(ii) Viscose staple fibre	150 m3/tonne of product
	(iii) Viscose filament yarn	500 m3/tonne of produced
7.	Tanneries	28 m3/tonne of raw hide
8.	Starch, glucose and related products	8 m3/tonne of maize crushed
9.	Dairy	3 m3/Kilolitre of milk
10.	Natural rubber processing industry	4 m3/tonne of rubber
11.	Fertilizer	
	(a) Straight nitrogenous fertiliser	5 m3/tonne of urea of equivalent produced
	(b) Straight phosphatic fertiliser (SSP & TSP) excluding manufacture of any acid	0.5 m3/tonne of SSP/TSP.
	(c) Complex fertilizer	Standards of nitrogenous and phosphatic fertilisers are applicable depending on primary product

Annexure II

MNES sponsored R & D projects for development of biomethanation technology (TERI, 1994)

Project Title	*Organization*	*Category*
Utilization of sludge gas for operation of gas turbine engines	NAL, Bangalore	A
Generation of biogas from aquatic weeds with special ref. to utilization of salvinia	Centre for Water Res. & Dev. Management, Kerala	C
Biogas production from banana in the scale up of bench scale experiments in the thermophilic digester	Vallabh Vidya Nagar, Gujarat	D
All-India co-ordinate project on biogas programme	IIM, Vastrapur, Gujarat	A
Mathematic modeling of biogas technology	IIT, Bombay	E
Domestic waste water treatment cum biogas generation at Sangli	Joglekar Sahakari Society Ltd., Sangli	A
Microbiological aspects of biogas technology	MACS, Pune	B
Demonstration of biogas plants based on castor cakes and non-edible wastes	APAU, Hyderabad	D
Utilization of willow-dust for the production of bioenergy to meet partly the energy	NIC, Bombay	A
Augmentation of biogas technology with special emphasis on substrate bio-degradation and	-	E
Validation and demonstration of diphasic anaerobic activated sludge process	-	D
Anaerobic activated sludge and immoblised reactor demonstration for water hyacinth based biogas systems	NEERI, Nagpur	B
Reuse of biogas slurry through waste stabilization algae and fish ponds and critical evaluation of its microbial quality and biochemical compost	Shri Paraskkathi College for Women, Tamilnadu	D
Study of plug flow type anaerobic digester and biogas purification utilization studies	Nagpur University, Nagpur	B
Use of biomass slurry from agriculture wastes and water-weeds as cattle feed	Pashu Palan Vikas Sansthan, Nainital	D

Fed-batch digestion studies on water hyacinth for biogas production in family size biogas plants	Regional Research Laboratory, Assam	D
Perfecting manufacturing techniques and modular design of ferro-cement biogas plant	Centre for Scientific Resaerch, Tamil Nadu	A
Setting up $10m^3$ biogas plant using water hyacinth	JNT University, Andhra Pradesh	D
Setting up a biogas digestion using non-edible castor cake	T.R.D.D.C., Pune	D
Development of clay biogas plants	Research Development Instutute, Bhopal	A
Development of continuous flow (plug flow) channel type digester for biogas production	IIT, Delhi	A
Process development using alternative feeds for biogas generation	Roorkee University	A
Optimization and demonstration of techniques of utilization of spent slurry to transportable product	Centre for Science for Villages, Maharashtra	D
Techno-economic evaluation of human excerta based large size biogas plants for community purposes	Sulabh Institute of Technical Research, Patna	A
Efficient utilization of agricultural waste for biogas generation	Rajendra Agriculture University, Bihar	D
Demonstration and evaluation of slurry effluent as manure from large sized biogas plants based on human excreta and water hyacinth	Sulabh Institute of Technical Research, Patna	D
Development of low cost biogas plants	Gujarat Vidyapith, Ahmedabad	A
Designing and development of biogas plant for paper industry waste using immobilised cells and dismastic system	Thapar Corporate Research & Development Centre, Patiala	A
Biogas augmentation by citrobector inter medius in industrial effluents (distillery & fruit processing)	M M Murugappa Chettiar Research Centre, Chennai	A
Standardization of developed biogas plant components and enrichment studies	Deptt. of agro-energy College of Agri Engg. Coimbatore	B
Isolation and study of celluloytic microganisms for their possible use in pretreatment	Mahatma Phule Agriculture University Maharashtra	B
Development and demonstration of project plant using composite agricultural waste	Sardar Patel Renewable Energy Research Institute	D
Operational research on the production of biogas and biomanure from willow dust by dry fermentation process	Cotton Technical Research Lab	B

Kinetics of biomethanation of leucaena leucocipmala and studies on methanogens	IIT, Madras	B
Microbiological studies of agricultural wastes	School of Biological & Earth Sciences	B
Development of mixed biogas cultures with wider adaptability for changes in temperature	A P Agriculture University	B
Production of biogas and transportable balanced fertiliser from slurry manure	B.I.T., Bihar	A
Solid fermentation of water hycinth to biogas	ASTRA, IISc, Bangalore	A
Solar aided package for biogas plants	Solar Engineering Unit, Pondicherry	A
Microbiological studies on the conversion of food processing waste	Centre for Technological Research Institute, Mysore	B
Microbiology anaerobical digestion and its oretreatment culture collection acid	Association for Cultivation Sciences, Pune	B
Development of single cell immobilization technology for cost effective methane recovery from distillery	IIT Bombay	A
Socio economic survey of biogas plants used in rural households	Annamalai University, Tamil Nadu	B
Biogas utilization in burners and engines	BHU, Varanasi	A
Studies on the microbiological aspects of biogas technology	Annamalai University, Tamil Nadu	B
Kinetics of biogas evolution from biomass wastes and its combustion properties	Gorakhpur University, Gorakhpur	B
Utilization of slurry (wet & dry application)	Rajasthan Agriculture University, Rajasthan	D
Studies on biogas storage distribution and utilization appliances	Dept of Electrical & Other Energy Sources, Akola, Maharashtra	A
Optimization and demonstration of techniques for utilization of spent slurry to convert it into dry transportable and saleable product	Centre of Science for Villages, Maharashtra	D
Field trials on the utilization of agriculture wastes for biogas production.	Bhartiya Agro Industries Foundation, Pune	E
A study in biomass plants in Bihar-their operation and impact on society	Sulabh Institute of Applied Research, Patna	B
Project on recovery of energy from sanitary landfills	IIT, Delhi	D
Installation of 100% biogas operated gensets development by BHEL, Hyderabad	BHEL, Hyderabad	D
Evaluation of techno-economic viability of available methane recovery technologies in	IIT, Bombay	E

Kinetics and dynamics of bio conversion of aquatic biomass for max retrieval of energy and biofertilizer	IIT, Delhi	B
New energy sources for biogas production	JNU, New Delhi	B
Testing evaluation and standardization of low pressure burner (biogas)	IIT, Delhi	E
Study on water hyacinth for metal pollution kendra - and subsequent utilization for energy in a biological system	Regional Research Laboratory, Hyderabad	B
Mechanism of lignocellulose degradation in anaerobic digestors	Tamil Nadu Agricultural University, Tamil Nadu	B
Handling & evaluation PF slurry for crop raising agronomy.	Annamalai University, Tamil Nadu	E
Procurement and field testing evaluation of swastik flexi biogas plants	Swastik Rubber Products Ltd, Pune	E
Bio-conversion of apple waste into hydrogen and methane	Delhi University, Delhi	A
BGP based on non-edible cakes at APAU	APAU, Hyderabad	D
Utilization of sludge gas for operation of gas engines	NAL, Bangalore	A
Energy recovery from water hyacinth using biphasic biogas technology	Sardar Patel University, Gujarat	A
Nightsoil based: biogas plants using H.D.P.E.	Dept. of Physics, School of Poona	D
Advanced studies on biogas technology	IISc, Bangalore	A
Development of plug flow tunnell type biogas digester	TECSOK, Bangalore	B
Enzymatic enhancement of biomass digestion to increase biogas production	Shivsadan Griha Nirman Sahakar Society Ltd, Sangli (MS)	B
Recovery of biogas from sanitary land fill	NEERI, Nagpur	A
Setting up of a pilot plant of 25 cu.m. capacity using willow dust for biogas generation at Udaipur cotton mills	CTAE, Rajasthan Agriculture University, Rajasthan	D
Pilot studies on biogas production and farmers level demonstration of research results	Bhartiya Agro-Industries Foundation, Pune	D
Studies on the kinetics of degradation leading to the nstallation of 50 cu. m biogas digestor	Tata Research, Development & Design Centre, Pune	B
Jtilization of slurry wet and dry application (Phase II)	Rajasthan Agriculture University, Rajasthan	A
Vlicrobiology of methane production and effect of race elements.	Osmania University, Hyderabad	E

Production of biogas from mixed biomass	Kalyani University, Kalyani (WB)	A
Bioenergy generation using plant and animal waste at Sanjay Gandhi Biological Park	Sulabh Institute of Research & Development, Bihar	D
Enzymatic enhancement of biomass digestion of increase biogas production.	Shivsadan Griha Nirman Society Ltd, Sangli	B
IBP based on horse dung at SVPMPA	NEDCAP, Hyderabad	D
IBP based on human excreta at 8 sites of Telgu Bala Mahila, AP	Telugu Bala Mahila, NEDCAP, AP	D
Hydrogen sulphide removal from biogas of CPIL distillery effluent	GEDA, Baroda	B
Setting up pilot plant based on sheep droping at central sheep wool research institute	Rajasthan Agriculture University, Rajasthan	D
Lab studies for assessing the feasibility of using diphasic process for bi-methanation of agricultural waste	Sardar Patel Renewable Energy Resarch Institute, Gujarat	A
Installation, monitoring and demonstration of biogas plant based on alternative feed stocks	Sardar Patel Renewable Energy Research Institute, Gujarat	E
Operation of AI-20 aero engine with sludge gas	NAL, Bangalore	A
Pilot studies on utilization of pressmud as a suppl. feed stock for biogas generation	Annamalai University, Tamil Nadu	D
Fuel and fertilizer from water hyacinth	TESCSOK, Bangalore	A
IBP based on canteen and kitchen waste	NEDCAP, Hyderabad	D
Garbage based biogas plant bardoli model	Kasturbagar Krishi Kashetra, Indore	A
Test kit for fermentation and methogenic anaerobes	Tamil Nadu Agriculture University, Tamil Nadu	E
Pilot trial of biogas plant	CEEISS, Nasik	E
Microbiology of methane production from cattle dung and human waste, piggery waste and SAGO industry effluent	Tamil Nadu Agriculture University, Tamil Nadu	B
Methanogenesis from agricultural byproducts	TERI, New Delhi	B
Search for alternative source of fuels from non-conventional energy sources	Kalyani University, Kalyani (WB)	B
Isolation and study of cellulolytic microorganisms for their possible use in pretreatment	Mahatma Phule Agricultural University	B
Night soil based system for Pandmarpur SGMSS	SGNSS Ltd, Sangli	D
Development rational decision criteria for the selection of biogas digesters	Pondicherry	B

Biogas generation using portable biogas plants for cattle camps at Atladara dist.	GEDA, Baroda	D
Anaerobic digestion of distillery effluent studies on scaled up pilot plants	Daurala Sugar Unit Works, Meerut	E
Methane gas recovery - a pilot plant study	EPRF, Sangli	D
Biogas plant at IAF, Saharanpur	Station Commander Gorakhpur	D
R&D on fixed film reactor technology	Polychem Limited, Maharashtra	A
Evaluation of deep poultry litter as feed stock for biogas production	Punjab Agriculture University, Ludhiana	E
Microbiological aspects of improved biogas production from agricultural waste	IARI, New Delhi	B
Studies on microbiological aspects of methane production	Annamalai University, Tamil Nadu	B
Use of biogas slurry in aquaculture	Central Institute of Fresh Water, Bhubaneshwar	A
Microbial process improvement of biogas digestors	National Dairy Research Institute, Kamal	B
Microbial studies for process improvement in anaerobic digestion	MACS, Pune	B
Methangens national culture collection and data base	MACS, Pune	B
Optimization of biogas production for forest waste through optimum retention period using	REC, CTAE, Udaipur	E
Pilot studies in methane generation from fruit and vegetable processing wastes	CFTRI, Mysore	A
Utilization of biogas plant slurry for mushroom cultivation	Punjab Agriculture University, Ludhiana	D
Treatment of kitchen waste and generation of biogas for hotel Blue Diamond, Pune	MEDA, Bombay	D
Demonstration of fixed film reactor technology for bio-methanation of hospital waste water	NEERI, Nagpur	D
Pilot project for total coverage of Dehu village for biogas plants	Pune	D
Setting up a pilot biogas plant based on camel dung	REC, CTATE, Udaipur	D
Installation of horse dung based BGP at HDA premises at Kharakwasla, Pune	BAIF, Pune	D
Microbial aspects of improved biogas production from agrucultural waste	IARI, New Delhi	E

Design and development of instumentation and systems for biogas technology	Nagpur University, Nagpur	B
Development of flexi biogas production system suitable for anaerobic biogasification of a	RRL, Assam	A
Generation of biogas from industrial wastewater (tannery wastes)	IIT, Madras	A
Studies for biogas systems based on slaughter house refuse at twin cities of Hyderabad and Secunderabad	NEDCAP, Hyderabad	E
Biomethanation of distillery effluent - a pilot plant study	Daurala Sugar Works, UP	A
Techno-economic study to assess the potential of cogeneration in Punjab	Punjab State Council for S&T, Chandigarh	B
Commercial model of nutrient technique for biogas generation and simultaneous treatment of	-	A
Two stage biomethanation of MSW to improve bioleachate production and biogas generation	IIT, Kharagpur	B
Mathematical modelling of landfill gas system	NEERI, Nagpur	B
Development of biogas plant for utilization of vegetable waste from agriculture produce market committee, Gultekadi Market Yard, Pune	MGSN, Pune	B
Prototype development of a biogas plant for agriculture residues using diphasic process	Sardar Patel Renewable Energy Research Institute, Gujarat	A
Retrofitting of existing 10 cu m cattle dung based biogas plant by agro waste based biogas plant	Sardar Patel Renewable Energy Research Institute, Gujarat	D
Microbiological, biochemical and fermentation studies on consortia developed for biogas production from food and agro-industrial wastes	CFTRI, Mysore	B
Operation and process control for biogas production from fruit and vegetable processing wastes in 25 cu.m. KVIC	CFTRI, Mysore	A
Pilot plant of 340 cu.m. capacity for generation of biogas from sugarcane pressmud	-	D
Pilot plant of 150 cu m capacity bio-methanation of sugarcane pressmud	Vasantadada Sehkari Coop. Sugar Mills, Sangli	D
Pilot plant of 360 cu.m. capacity bio-methanation of sugarcane pressmud	Ugar Sugar Works Ltd.	D
Use of immoblized cell technology for methane through various fixed film reactors	Punjabi University, Patiala	B

Setting up of 25 cu.m capacity willow dust based biogas plant at Kharar textile mills, Kharar	NTC, New Delhi	D
Setting up of 90 cu.m. capacity willow dust based biogas	NTC, Indore	D
Characterization of wastes of different origin for biochemical conversion establish performance parameter and design criteria	Centre for Biochemical Technology Delhi	B
Development of plug flow digester for biogas production from fibrous substrates	BAIF, Pune	B
Demonstration of pressmud based biogas production technology (IEP) at Yashwant Sahakari Sakhar Karkhana, Pune	BAIF, Pune	D
State of art on anaerobic technologies preparation of reports	NEERI, Nagpur	B
Publication of technical documents on biogas generation from alternative feedstock - a new concept	Annamalai University, Tamil Nadu	B
Field trials on biomass production from mango processing waste in 25 cu.m. digesters at the fruit and vegetable plant of NDDB, New Delhi	CFTRI, Mysore	E
Development and performance evaluation of various high rate reactors for methane recovery from industrial organic effluents	Sardar Patel Renewable Energy Research Institute, Gujarat	A
Standardization of technology on the utilization of sugarcane filtercake (presspud) for biogas generation	Annamalai University, Tamil Nadu	B
Tanning industry pollution control and abatement - a state of art	NEERI, Nagpur	B
Case study a performance evaluation of pilot projects for waste recycling	Consolidated Energy Consultants, Bhopal	E
Setting up of biogas plants (3 units based on vegetable wastes)	Special Schemes & IRD Deptt., Rajasthan	D
Compiling Urja Bharati issue of GEDA	Gujarat Energy Development Agency, Baroda	B

A - applied research
B- Basic research
C-Commercial research
D-Demonstration
E-Evaluation,testing,monitoring etc
Source TERI, 1994

Annexure III

Questionnaire

Energy from Waste: Survey

Tata Energy Research Institute, New Delhi

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1. Name of the industry :________________________

2. Factory address of the industry :________________________

:________________________

:________________________

3. Scale of industry : a) Large b) Medium c) Small

4. Products manufactured*

Name of Products	Installed capacity	Actual production in the year 19...	Number of days of production during the year

If necessary, please provide information on a separate sheet.

. Raw materials used*

Products Name	Name of the raw materials	Qty. Per unit production

If necessary, please provide information on a separate sheet.

6. Brief description about unit operations for each product

(*You may use separate sheet, provide process flow/material balance diagrams*)

7. Effluent generation*

Steam No.	Source (Name of the operation)	Qty. per day	Flow intermittent or continuous	Charateristics (Temp, BOD, COD,pH,TS,VS,heavy metals, fats, protiens, N, P etc.)	Weather ETP Installed (yes/No)
Stream 1					
Stream 2					
Stream 3					
Combined					

* use separate sheet if necessary

Details of Effluent Treatment Plant (ETP)*

Treatment unit	Installed capacity	Present Flow	Input wastewater characteristics	Treatment efficiency	Any other salient feature of the unit

use separate sheets if necessary, you may also provide flow diagram.

Are you Satisfied with the performance of the (ETP) : Yes/No

(If No, please give the reasons)

10. Name and address of consultant who had Installed the ETP at your industry : ______________________________

: ______________________________

Annexure IV

Energy from Waste: Survey

Tata Energy Research Institute, New Delhi

Note: Use separate sheet for each industrial/municipal sector

1. Name of the sector : ____________________

2. Clients served in the above sector*

S No.	Client's name	Complete Address with phone & FAX number

* attach separate sheet if necessary

3. Typical charateristics of the wastewater that you have observered in the above industrial sector

4. What in your opinion is the Qty. of wastewater per unit of production : ________________

5. Treatment schemes suggested/installed

a) Pre-treatment units :

b) Anaerobic reactor configuration :

c) Post-treatment units :

d) Biogas treatment & utilisation :

6. Whether the anaerobic reactor technology is developed by you ? Yes/No

A) If No, whether your collaborator is Indian or foreigner.

7. Typical design features of the reactor that you may wish to quote.

8. Performance of the Anaerobic reactor :

BOD removal : _________

COD removal : _________

Gas yield : _________

9. What in your opinion are the challanges associated with the adoption of anaerobic technology in this industrial sector?

10. What research activities are needed for improvement in anaerobic process for this industrial sector ?